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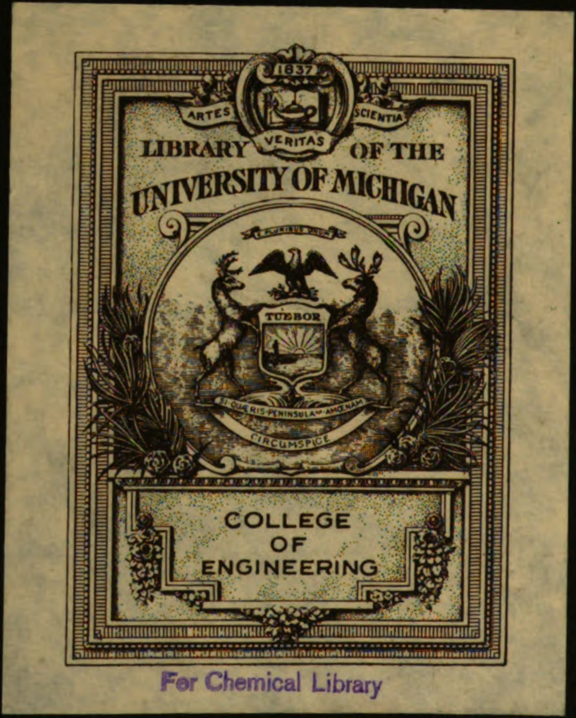

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OF THE

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VOL. XCIX.

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GEORGE C. LLOYD

SECRETARY

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PREFACE.

This volume of the *Journal of the Iron and Steel Institute* contains the report of the proceedings at the Annual Meeting held in London in May 1919, together with the papers read on that occasion and the discussions and correspondence to which they gave rise.

Papers on Electric Steel Furnaces read at the joint session with the Institution of Electrical Engineers will, it is understood, be published, together with the discussion and correspondence thereon in the *Journal of the Institution of Electrical Engineers.*

A report of the proceedings and speeches at the Annual Dinner of the Institute held in the Guildhall on May 8th, and the Notes on the Progress of the Home and Foreign Iron and Steel Industries and the Bibliography, complete the current volume.

28 Victoria Street, London, S.W. 1.
August 1919.

369271

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THE

IRON AND STEEL INSTITUTE.

SECTION I.

MINUTES OF PROCEEDINGS.

ANNUAL MEETING, 1919.

The Fiftieth Annual Meeting of the Iron and Steel Institute was held at the Institution of Civil Engineers, Great George Street, Westminster, on Thursday and Friday, May 8 and 9, 1919, Mr. C. P. Eugène Schneider, President, in the Chair.

The Minutes of the previous Meeting, held at the Institution of Civil Engineers on September 12 and 13, 1918, were taken as read and signed as a correct record.

Appointment of Scrutineers of the Ballot.

Messrs. Wilson Cross (London) and G. Watson Gray (Liverpool) were appointed scrutineers of the ballot for the election of new members and associates, and on the completion of their scrutiny announced that the following ninety-seven candidates for membership and eleven candidates for the associateship had been duly elected :

Members.

Name.	Address.	Proposers.
Abell, W. S.	71 Fenchurch Street, London, E.C.	J. T. Milton, Sir R. A. Hadfield, Bt., H. Ruck-Keene.
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Hodgson, Roland .	Guide Bridge Iron Works, nr. Manchester.	C. Scott, L. Rothera, J. P. Bedson.
Hopkins, George A. .	The Carnegie Steel Co., Munhall, Pa., U.S.A.	H. P. Tiemann, C. F. W. Rys, J. S. Unger.
Hudson, *Major* Noel, D.S.O., p.a.c. R.A.	Research Dept., Royal Arsenal, Woolwich	F. W. Harbord, C.B.E., W. R. Lysaght, C.B.E., *Major* W. H. Merrett.
Hutchinson, Fred Ronald	Birtree Lane, Harrowgate Hill, Darlington	H. Frankland, J. E. Stead, J. Lloyd Bentley.

Name.	Address.	Proposers.
Irwin, Charles Armstrong	Kalimati, B.N. Railway, India	J. O. Arnold, E. J. Barnes, A. McWilliam.
Isaac, Sidney Russell	52 Iorwerth Street, Manselton, Swansea	R. Graham, G. W. Lewis, T. O. Lewis.
Jayne, James Henry .	25 Market Street, Llanelly, South Wales	J. J. Stevenson, R. Graham, J. C. Godsell.
Jermain, William Morgan, B.Sc.	Metallurgical Laboratory Research Dept., Royal Arsenal, Woolwich, S.E. 18	H. Moore, R. Mather, H. I. Coe.
Jewell, William Ralph, B.Sc., B.Met., A.I.C.	19 Noble Street, Geelong, Victoria, Australia	T. Baker, J. O. Arnold, Sir W. Beardmore, Bt.
Jo, Masatoshi . .	Royal School of Mines, South Kensington, London, S.W.	T. Turner, J. E. Stead, G. Oishi.
Johnson, Charles Morris, Ph.M.	Crucible Steel Co. of America, Pittsburgh, Pa., U.S.A.	J. O. Arnold, W. J. Green, B. Talbot.
Jones, Frederick George	33 Royal York Crescent, Clifton, Bristol	J. S. G. Primrose, H. S. Primrose, F. B. Oakes.
Jones, Gethin . .	Manager, Open Hearth Dept., Dowlais Cardiff Works, Cardiff	E. C. Greig, C. G. Atha, James Henderson.
Keeney, Robert Mayo	Iron Mountain Alloy Co., 1125 York Street, Denver, Colorado, U.S.A.	B. Stoughton, F. Crabtree, D. A. Lyon.
Lee, Wee Kua . .	Mass. Institute of Technology, Cambridge, Mass., U.S.A.	H. Fay, Sir W. Beardmore, Bt., A. Cooper.
Leslie, Robert Macbeth	88 North Road, Highgate, London, N. 6	Sir R. A. Hadfield, Bt., F. W. Harbord, C.B.E., A. G. M. Jack.
Lewis, *Capt.* William Edmund Jenkyn, B.Sc.	Hazelhurst, Ebbw Vale, Mon.	Frederick Mills, G. Barrett, R. A. Lewis.
Lindemuth, Francis Lloyd	Tata Iron & Steel Co., Sakchi, India	S. M. Marshall, H. M. S. Tuckwell, Sir W. Beardmore, Bt.
Lloyd, Richard . .	29 Rue de Mogador, Paris (IXe), France	J. F. Melling, J. F. Moss, J. S. Watson.
Lobley, Henry D., M.Sc.	122 Aldeburgh Road, Leiston, Suffolk	T. Turner, F. E. Walker, F. B. Oakes.
Lockley, Herbert Hirst Lambert, Assoc.Met.	Moorland, Chatsworth Road, Totley Rise, Sheffield	A. Senior, T. Swinden, G. E. Senior.
Lones, John Hunt .	Park House, Blaenavon, Mon.	H. Spence Thomas, G. Mure Ritchie, H. Jeans.
McLean, Thomas .	Heathfield, Mickleover, Derby	Sir H. Fowler, K.B.E., Sir A. S. Haslam, H. C. D. Scott.

NAME.	ADDRESS.	PROPOSERS.
McMaster, Ross H. .	The Steel Co. of Canada, Ltd., Montreal, Canada	F. H. Whitton, *Col.* E. Carnegie, F. W. Harbord, C.B.E.
Martin, Francis Grimshaw, B.Sc., F.I.C.	Seaton Buildings, 17 Water Street, Liverpool	J. L. Haughton, D. Hanson, Phoebe M. C. Routh
Mills, Frederick .	Heathfield, Fforestfach, nr. Swansea	J. C. Davies, *Col.* J. R. Wright, D. E. Roberts.
Moody, Chester Sherman	2606 South Dupont Avenue, Minneapolis, Minn., U.S.A.	H. C. H. Carpenter, Sir W. Beardmore, Bt., A. Cooper.
Oving, Herman Ellens, Jun.	31-32 Gelderschekade, Rotterdam	*Lieut.-Col.* M. H. Bell, *Major* A. Dorman, W. R. Makepeace.
Peakman, Percy .	151 Barton Road, Stretford, Manchester	J. E. Hurst, C. A. Edwards, W. Whiteley.
Robertson, Frederick Duncan Struan	P.O. Box 273, Toronto, Canada	A. Campion, E. Humbert, P. Harden.
Rose, *Lieut.* William Henry, R.A.F.	13 Arnold Mansions, Queens Club Gardens, W. Kensington, London, W. 14	Sir R. A. Hadfield, Bt., A. G. M. Jack, F. W. Harbord, C.B.E.
Russell, John . .	41 Endcliffe Rise Road, Sheffield	Cosmo Johns, R. B. Jackson, A. Williamson.
Russell, Thomas Francis	131 Steade Road, Sheffield	J. O. Arnold, E. H. Saniter, J. E. Stead.
Scott, *Major* Henry Granville	"Beechcroft," Marton, S.O., Yorks	G. Ritchie, J. C. Jones, D. Sillars.
Shepherd, Benjamin Franklin	214 Lewis Street, Phillipsburg, N.J., U.S.A.	J. A. Mathews, H. A. Pardee, W. B. Brookfield.
Smith, Richard Tilden	70 Lombard Street, London, E.C.	Sir Hugh Bell, Bt., A. Cooper, Henry Louis.
Taylor, George . .	48 Glencoe Road, Sheffield	H. Brearley, M. R. Mainprice, A. W. Brearley.
Teasdale, Thomas Bonnor	28 Endcliffe Terrace Road, Sheffield	Sir W. H. Ellis, G.B.E., G. S. Packer, M. E. Unwin.
Thickins, David .	Beaufort Road, Sirhowy, Mon.	Frederick Mills, F. W. Daw, G. Barrett.
Thomas, Albert .	"Glenmore," 17 Holland Street, Ebbw Vale, Mon.	Frederick Mills, R. A. Lewis, F. W. Daw.
Tinsley, Matthew Ralph	Glan Ebbw House, Victoria, Mon.	N. K. Turnbull, G. Barrett, F. W. Daw.
Trumper, Thomas William Walwyn	4 Queen Street, Victoria, Mon.	Frederick Mills, G. Barrett, F. W. Daw.
Vandeleur, *Lieut.-Col.* Henry Martley, R.A.	46, Devonshire Street, Portland Place, London, W. 1	F. W. Harbord, C.B.E., W. R. Lysaght, C.B.E., *Major* W. H. Merrett.
Venton, Horace William	Oakcroft, Grange Park, London, N.	J. Jefferson, J. O. Arnold, A. McWilliam.
Voorhees, Edward C. .	Erie Forge Co., Erie, Pa., U.S.A.	D. J. McAdam, Jun., C. F. W. Rys, H. P. Tiemann.

NAME.	ADDRESS.	PROPOSERS.
Wabanabi, Saburo	Tokyo University, Tokyo, Japan	Sir R. A. Hadfield, Bt., I. B. Milne, W. J. Dawson.
Walker, Edwin	"Clivedon," 10 Tapton House Road, Sheffield	J. E. A. Blyde, A. Senior, M. Wardlow.
Wells, George William	155 St. Lawrence Road, Tinsley, Sheffield	I. B. Milne, W. J. Dawson, L. J. Swift.
Whitfeld, Hubert Edwin, B.Eng.	The University of Western Australia, Perth, Western Australia	C. G. Atha, J. Henderson, E. C. Greig.
Widdas, Southern	36 Springfield Lane, Ipswich	J. S. G. Primrose, H. S. Primrose, J. H. Lavender.
Williams, William Ellis, B.Sc.	Aeronautical Inspection Dept., Clement's Inn, Strand, London, W.C. 2	Sir R. A. Hadfield, Bt., A. G. M. Jack, I. B. Milne.
Williamson, Thomas Ogilvie	Burnham, Pa., U.S.A.	O. C. Skinner, L. H. Fry, H. V. Wille.
Wilson, *Capt.* Arthur Kingsford	Messrs. Spear & Jackson, Ltd., Aetna Works, Sheffield	A. Good, G. E. Senior, V. Proctor.
Wilson, Robert Martill, A.M.I.E.E.	"The Nook," Ebbw Vale, Mon.	Frederick Mills, R. A. Lewis, F. W. Daw.
Woods, Roland	National Federation of Iron and Steel Mfrs., Temple Bar House, Fleet Street, London, E.C. 4	Sir Hugh Bell, Bt., B. Talbot, W. Thornycroft.
Wooldridge, William John	134 Appleton Avenue, Pittsfield, Mass., U.S.A.	J. A. Capp, J. W. Richards, F. Crabtree.
Worrall, Stanley	Priory House, Sharrow, Sheffield	J. O. Arnold, L. Dufty, B. W. Winder.

ASSOCIATES.

Cook, Maurice	13 Victoria Place, Hartlepool	C. A. Edwards, W. Whiteley, J. H. Andrew.
Cooke, Henry Aitken	Glen View, Court Sart, Briton Ferry, Glam.	J. C. Godsell, H. Eccles, R. P. Bevan.
Elcock, Edward Wilson	18 Tylney Road, Park, Sheffield	J. H. S. Dickenson, J. E. Howarth, H. Lodge.
Gresty, Colin	The North Eastern Marine Engineering Co., Ltd., Wallsend-on-Tyne	J. T. Dunn, H. J. Young.
Jackson, Stanley Alexander	5 Wharncliffe Road, Broomhall Park, Sheffield	F. Atkinson, A. W. Brearley, W. H. Hatfield.
Knoyle, William Leonard	The Sanctuary, Loughor, Glam.	J. C. Davies, J. C. Godsell, J. E. Torbock.
Lewis, John Samuel	35 Pemberton Street, Llanelly	T. Crosby, A. Wright, J. C. Godsell.

NAME.	ADDRESS.	PROPOSERS.
Squire, Edward Samuel	4 Hopkin Street, Brynhyfryd, Swansea	A. Hethey, J. E. Torbock, J. C. Godsell.
Stephenson, Harold .	4 Toller Drive, Toller Lane, Bradford	W. West, G. J. Stock, W. H. Poole.
Thomas, Alfred John Leslie	45 Neath Road, Briton Ferry	H. Davies, A. R. Roberts, J. C. Godsell.
Wright, Ronald Blythe	97 Scott Road, Sheffield	E. Dawtry, F. Atkinson, A. W. Brearley.

The SECRETARY read the Report of Council for the year 1918, which will be found on pp. 14–27.

STATEMENT OF ACCOUNTS.

The HONORARY TREASURER (Mr. Illtyd Williams), in presenting the Statement of Accounts for 1918, said the past year was not one he could whole-heartedly congratulate himself upon. The income side showed a fairly satisfactory state of affairs, as there was an increase under almost every separate heading as compared with 1917. The total, £5792, was £365 more; which, it might be noted, was the highest figure reached in any year during the life of the Institution. The total expenditure, £6128, exceeded, however, that for the previous year by £926, and showed a deficit of £336 instead of a surplus of £224 as in 1917. The chief items constituting that increase were the printing of the Journal, which had increased by £643; salaries, which had increased by £246; stationery, which had increased by £147; and postage and receipt stamps, which had increased by £32. In other directions savings had been made, the chief being in the item of contributions from the Institute funds to other Societies for special objects. It was possible that the general income of the Institute might, before long, be relieved from the strain of such contributions. The increases were due to war conditions, and had been unavoidable. The debt owing to the bankers on account of £1000 5 per cent. War Loan was discharged during the year and £400 invested in 5 per cent. War Bonds; otherwise the invested funds of the Institute and of the Carnegie Research Scholarship Fund stood unaltered. The Carnegie Fund figures showed a surplus of income over expenditure amounting to £479. There were fewer applications for grants from that fund during the last few years, as most of those who were entitled to make applications were serving their country in one capacity or another. With the advent of peace probably more claims would be made, and the position would alter. The year had been an anxious one for all those who were concerned with the finances of the Institute, and he would like to testify to the efforts that had unceasingly been made in the direction of securing economy by the Secretary, Mr. Lloyd, and his staff. In concluding, it might probably be not unfitting to say something concerning those members of the staff who had served their country under arms. Mr. Arthur Dowd, who came to the Institution on leaving school twenty-six years ago, unfortunately had not returned. After obtaining his discharge in France, and when on the way home, he was attacked by illness and died in hospital. He was sure the members of the Institute would extend their sympathy to his widow and family. Mr. Richard Elsdon, who was severely wounded in August 1917, had been discharged from hospital and had returned to take up his duties as librarian, and to him the members offered their congratulations.

The PRESIDENT then moved the adoption of the Report of the Council and of the Statement of Accounts as presented (see pp. 28-31), the motion being carried unanimously.

BESSEMER MEDAL.

The PRESIDENT then presented a replica of the Bessemer Medal to Mr. Auguste Greiner, who attended on behalf of himself and his brother, Mr. Leon Greiner, who was unavoidably prevented from being present. He said that just six years ago the original Medal had been presented to the recipient's father, Dr. Adolphe Greiner, in recognition of his eminent achievements in the metallurgy of iron and steel. In the year following Dr. Greiner had honoured the Institute by accepting the Presidency. No one at that time foresaw the calamity which was destined so soon to overtake his devoted country. It was well known to all the members how the city of Liége, and with it the great undertaking with which Dr. Greiner was associated so long, was overwhelmed early in the war, after a truly heroic resistance. It was also well known how Dr. Greiner had bravely faced the storm, encouraging others by his own indomitable courage, and carrying on the direction of the works in the face of unheard-of oppression and difficulties, and how, finally, he succumbed, under the burden of his heavy responsibilities, and died a victim of the war and of his devotion to duty. It came to the knowledge of the Institute that he had been forcibly removed from his home for a time and was treated as a common prisoner. His residence was in the meantime occupied by officers of the invading army. On Dr. Greiner's return he found that various objects of value, amongst which was the Bessemer Medal, had disappeared—appropriated, or it might frankly be said, stolen, by some officer of the ex-Kaiser; a practice which both Belgians and French had good reason to know was afterwards largely extended wherever the invaders set foot. The Council determined as soon as conditions permitted to present a replica of the Medal to Dr. Greiner's son, Mr. Leon Greiner, the worthy successor of his father. The new Medal differed from the original in one respect only: it bore a brief inscription engraved round the edge recording the history of the former Medal: "A replica of the Medal stolen by the Germans during their unjust occupation of Liége, 1914–1918." In the name of the Institute he presented to Mr. Auguste Greiner the copy of the former Medal, in memory of his noble father; he begged him to accept it for his brother and himself with the sincerest good wishes of the members of the Institute, and he trusted his brother might long be preserved to carry on the direction of the establishment which Dr. Adolphe Greiner had ruled for over a generation.

Mr. AUGUSTE GREINER, speaking in French, thanked the President, Council, and Members for their kindness, on behalf of himself and the other members of his family. He regretted his brother had been unable to attend, but promised to transmit to him both the Medal and the good wishes of the Institute, as conveyed by its distinguished President.

The PRESIDENT said that, by the unanimous decision of the

Council, the Bessemer Medal for the year 1919 had been awarded to the eminent Italian metallurgist, Dr. Cav. Federico Giolitti, managing director of the well-known firm of Messrs. Gio. Ansaldo and Co., Ltd., Genoa, in recognition of his distinguished services in the advancement of the metallurgy of iron and steel. Dr. Giolitti was well known to the members on account of his important work on the cementation and heat treatment of steel. Unfortunately he had been detained by pressing engagements which had prevented his attendance that day, and it was therefore proposed to postpone the actual presentation of the Medal to a future occasion.

FREEDOM OF THE BLACKSMITHS COMPANY.

The SECRETARY said he had been asked by the President to announce that the Council had received from the Prime Warden of the Court of the Worshipful Company of Blacksmiths an offer which was contained in the following resolution passed at a meeting of the Court of the Company on October 3 last:

> "That the freedom of the Worshipful Company of Blacksmiths, together with a gold medal bearing the Arms of the Company be presented annually to a student or to a contributor of a paper to the Iron and Steel Institute. The award will be at the discretion of the Council in consultation with the Warden of the Court of the Blacksmiths Company."

Dr. ARTHUR COOPER (Past-President) announced that a large number of the Members of the Council were present on the previous day at a very pleasing ceremony, when the Prime Warden and Court of the Worshipful Company of Blacksmiths presented the freedom of the Company to the President, Mr. Eugène Schneider, and to the immediate Past-President, Sir William Beardmore. The resolution of the Company really amounted to a closer association between the Company and the Institute, and he was sure that nothing but good could result from such an association. He had great pleasure, therefore, in proposing a very hearty vote of thanks to the Blacksmiths Company.

The motion was carried unanimously.

LETTERS OF CONGRATULATION.

The **SECRETARY** then read letters from the Institution of Mining and Metallurgy, and from the Institute of Metals, congratulating the Iron and Steel Institute on the attainment of its Jubilee, and expressing cordial appreciation of its great services to the cause of metallurgy during the fifty years which had elapsed since its foundation in 1869.

CARNEGIE SCHOLARSHIP AWARDS.

The **SECRETARY** read the following list of awards of Carnegie Research Scholarships for the current year:

After carefully investigating the applications the Committee have recommended that grants of the value stated below be awarded to each applicant, namely:

ALASTAIR THOMAS ADAM (Messrs. Brunton, Musselburgh), £100, for an investigation on "The relation of heat treatment to cold work in hypo-eutectoid and eutectoid steels, including the effect of heat treatment after cold work."

DR. J. O. ARNOLD, F.R.S. (Sheffield University), £100, towards the expenses of the high-speed steel research carried out at Sheffield University, the results of which have been presented in a paper to the Iron and Steel Institute.

FRANK BAINBRIDGE (the Skinningrove Iron Co., Ltd.), £100, to enable him to continue his investigations on "The effect of fluorspar additions on the phosphates of basic slag" (the applicant was previously awarded £100 in 1917 for this investigation, the results of which have been presented in a preliminary Report).

HOWARD J. STAGG, Jun. (the Halcomb Steel Co., Syracuse, N.Y.), £100, to carry out an investigation on "Brittleness in steel at blue-heat temperatures."

Mr. **AUGUSTE GREINER** (Antwerp) then read a paper by his brother, Mr. Leon Greiner (Seraing, Liége) on "The Condition of Belgian Iron and Steel Works after the German Occupation."

A paper by Mr. L. C. Harvey (London) on "The Use of Powdered Coal" was then read and discussed, after which the meeting was adjourned to the following morning.

JOINT SESSION WITH THE INSTITUTION OF ELECTRICAL ENGINEERS.

In the afternoon of Thursday, May 8, a joint session was held, by invitation of the Institution of Electrical Engineers, to read and discuss a symposium of papers on electric steel furnaces. The session was held at the Institution of Civil Engineers, and was opened by Mr. Eugène Schneider, President of the Iron and Steel Institute, supported by Mr. C. H. Wordingham, C.B.E., President of the Institution of Electrical Engineers, and many Vice-Presidents and Members of Council of both Institutions. After the formal opening, the President vacated the Chair in favour of the President of the Institution of Electrical Engineers, who presided during the remainder of the session.

The following papers were read in abstract and discussed:

"Developments in Iron and Steel Electric Furnaces," by Mr. J. BIBBY.
"The Booth Hall Electric Furnace," by Mr. W. K. BOOTH.
"Application of Electrical Energy to the Melting of Metals," by Mr. H. A. GREAVES.
"Electric Furnaces in the United Kingdom, 1918," by Mr. R. G. MERCER.
"New Type of Electric Furnace," by Mr. AXEL SAHLIN.
"Large Electric Steel-Melting Furnaces," by Mr. VICTOR STOBIE.

For a report of the proceedings and the text of the papers read and of the discussion, members are referred to the *Journal of the Institution of Electrical Engineers*, in which they will be reprinted *in extenso*.

The meeting was resumed at 10 A.M. on Friday, May 9, the Chair being taken by the President. The following papers were then read and discussed:

"A Review of the Work of the United States National Research Council," by Professor H. M. HOWE (Columbia University, New York).
"Modern Steel Metallurgy," by Mr. C. H. F. BAGLEY (Stockton-on-Tees).
"The Acid Hearth and Slag," by Messrs. J. H. WHITELEY and A. F. HALLIMOND, M.A. (Stockton-on-Tees).
"Macro Etching and Printing," by Mr. J. C. W. HUMFREY.

"The Manufacture and Working of High-Speed Steel," by Mr. J. H. ANDREW, D.Sc., and G. W. GREEN (Armstrong, Whitworth and Co., Ltd., Openshaw).

"Some Points in the Manufacture of Files," by Mr. G. TAYLOR (Sheffield).

"Improvements in the Case-Hardening Process," by Messrs. D. HANSON and J. E. HURST.

The sessions were resumed in the afternoon, Dr. J. E. Stead, F.R.S., Vice-President, occupying the Chair. The remaining papers, which were taken as read, comprised:

"Molecular Constitutions of High-Speed Tool Steels, and their Correlations with Lathe Efficiencies," by Messrs. J. O. ARNOLD and F. IBBOTSON.

"Note on the Liquidus in the Iron-Carbon Diagram," by Mr. G. CESARO

"Estimation of Phosphorus in the Presence of Tungsten," by Messrs. G. WATSON GRAY and JAMES SMITH.

"On the Non-Allotropic Nature of the A2 Transformation in Iron," by Mr. K. HONDA.

"Carburisation of Iron at Low Temperatures," by Dr. A. McCANCE.

"An Experimental Investigation of the Influence of the Rate of Cooling on the Hardening of Carbon Steels," by Messrs. A. M. PORTEVIN and M. GARVIN.

"On Graphitisation in Iron-Carbon Alloys," by Messrs. K. TAWARA and G. ASAHARA.

"Deoxidation, and the Influence of Lime on Equilibrium in the Acid Open-Hearth Furnace," by Mr. B. YANESKE.

On the motion of the CHAIRMAN, the best thanks of the meeting were accorded to the various authors for their kindness in presenting the papers.

The CHAIRMAN also proposed that the thanks of the Institute be given to the Council of the Institution of Civil Engineers for the use of their rooms for the purpose of the meeting.

Dr. ROSENHAIN seconded the motion, which was carried unanimously, and also moved a vote of thanks to Dr. Stead for presiding at the afternoon meeting.

The motion having been carried unanimously, the CHAIRMAN, in reply, thanked the members for their appreciation, and the proceedings then terminated.

REPORT OF COUNCIL.

THE Council have pleasure in submitting to the members of the Iron and Steel Institute at this, the Fiftieth Annual General Meeting, their Annual Report of the work and progress of the Institute during the year 1918.

PRESIDENCY OF THE INSTITUTE.

At the Annual Meeting on May 2, Mr. Eugène Schneider entered into office as President, in succession to Sir William Beardmore, Bart. His accession to the Presidential Chair was warmly welcomed by the members as a mark of the close co-operation between the metallurgists of France and Great Britain, in their common resolve to devote their energies to the assistance of their respective Governments in the prosecution of the War to a successful and speedy termination.

ROLL OF THE INSTITUTE.

There were 161 new members elected during the year, the largest number added to the roll in any one year since the foundation of the Institute fifty years ago. The list of candidates for election at the Autumn Meeting included five ladies, all of whom were duly elected. While to the new Associate class ten new Associates were elected during the year. The total membership of the Institute on December 31, 1918, was—

Patron	1
Honorary Members	4
Life Members	70
Ordinary Members	1963
Associates	60
Total	2098

There have been twenty-one resignations of membership during 1918, and the names of seven members have been removed from the list owing to the non-payment of subscriptions.

During the year the deaths of thirty-three members have been reported, the names of whom are recorded in the following list:

Armstrong, P. T. (Barnsley, Yorks)	...
Barker, James (Todmorden, Lancs)	March 12.
Bock, P. H. (Fagersta, Sweden)	...
Booth, William (Rodley, Leeds)	March 23.
Carnahan, R. B. (Middletown, Ohio)	June 22.
*Crawshay, W. T. (Reading)	September.
Crosland, J. F. L. (Hale, Cheshire)	October 21.
Cubillo, *Major-General* L. (Madrid)	December 15.
Cuthill, William (Uddingston, N.B.)	February 7.
Despaigne, H. (London)	September.
Dickinson, John (Ulverston)	March 24.
Douglas, James, LL.D. (New York)	June 25.
Gjers, L. F. (Middlesbrough)	February 4.
Hartshorne, J. (Pottstown, U.S.A.)	August 24.
*Hewlett, A. (Warwick)	September
Hingley, Sir G. B., Bt. (Dudley)	August 19.
Hopkinson, *Major* B., F.R.S. (Cambridge)	August 27.
Hunsiker, Colonel Millard (London)	October 11.
Hutchinson, T. C. (Saltburn)	October 17.
Jones, Greville T. (Middlesbrough)	March 6.
Jones, Thomas Herschel (Swansea)	January 18.
Keen, A T. (Birmingham)	June 27.
*Lloyd, Samuel (Birmingham)	February 26.
Morris, William (Briton Ferry)	June 15.
Paterson, J. (Carlisle)	September 6.
Pegler, T. B. (London)	...
Percy, T. M. (Wigan)	October 22.
Reynolds, A. (Brighton)	December 11.
Roberts, C. W. (Stourbridge)	September 25.
Rollin, F. T. (Sheffield)	April 4.
Schneider, *Lieut.* H. P. (Paris)	February 23.
Schneider, W. M. F. (Barrow-in-Furness)	May 3.
Shirley, F. L. (Briton Ferry)	August 1.

The death of the following member occurred in 1916 but was not noted in the Report of Council for that year:

Warocqué, Raoul (Mariemont, Belgium).

Lieutenant Henri P. Schneider, who was a cavalry officer in the French Army and was attached to the Flying Corps, was the eldest son of the President, C. Eugène Schneider, and a partner in his father's firm. He was killed in action on February 23, 1918. Mr. F. L. Shirley, of Briton Ferry, was killed in action on August 1, 1918, and Major Bertram Hopkinson was fatally injured in an accident while flying near London on August 27, 1918.

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* Original Member.

HONOURS CONFERRED UPON MEMBERS OF THE INSTITUTE.

The Council have pleasure in placing on record the following honours and distinctions which have been conferred upon members and associates of the Institute during the year:

Sir Hugh Bell, Bart., Past-President, has had conferred upon him the Companionship of the Order of the Bath. Professor H. Hubert and Mr. John Craig have had conferred on them Companionships of the Order of the British Empire. Mr. Pierre Breuil and Lieutenant Jean Schneider have been appointed Chevaliers of the Legion of Honour. Lieut.-Colonel J. G. Needham has been awarded the Distinguished Service Order, and Lieutenant Charles Schneider the Croix de Guerre. The Military Cross has been conferred on Captain F. Webster.

Professor J. W. Richards has been appointed Member of the Civilian Naval Consulting Board of the United States Government.

FINANCE.

The statement of accounts for the year 1918 has been verified by Messrs. W. B. Keen & Co., the auditors of the Institute, in the usual manner, and is now presented to the Meeting by the Hon. Treasurer. The accounts show that the total receipts of the Institute during the year under review, but excluding the income derived from the Carnegie Research Fund, were £5792. The expenditure during that period was £6128. The comparative figures for recent years are as follows:

	Income.	Expenditure.
1914	£5310	£4701
1915	4816	4275
1916	4767	4208
1917	5427	5202

The receipts on account of the Carnegie Research Fund were £1009 and the expenditure was £530, the surplus income over expenditure being £479.

MEETINGS.

The Annual Meeting took place on Thursday and Friday, May 2 and 3, 1918, and the Autumn Meeting was held on September 12 and 13. Both meetings were as usual held by kind permission of the Council of the Institution of Civil Engineers at the house of their Institution in Great George Street.

Mr. Eugène Schneider presided at both meetings, the full proceedings of which are reported in Nos. I. and II. of the Journal for 1918. Thirty-five papers were contributed to the proceedings at the two meetings, together with a Report of Committee No. 2 on Blast-Furnace Practice, which with the Presidential Address makes a total of thirty-seven communications.

The following is a list of the papers and reports presented at the meetings in question :

Presidential Address. By Mr. C. EUGÈNE SCHNEIDER.

Report of Blast-Furnace Committee: "Practical Points affecting Yield and Efficiency of Blast-Furnaces."

Papers:

1. "Principles of Open-Hearth Furnace Design." By C. H. F. BAGLEY.
2. "Damascene Steel." By Colonel N. BELAIEW.
3. "The Rate of Change at 100° C. and at Ordinary Temperatures in the Electrical Resistance of Hardened Steel." By E. D. CAMPBELL.
4. "Some Experiments on the Reaction between Pure Carbon Monoxide and Pure Electrolytic Iron below the A1 Inversion." By H. C. H. CARPENTER and C. COLDRON SMITH.
5. "Influences of Hot Working on the Qualities of Steel." By G. CHARPY.
6. "Importance of Coke Hardness." By G. D. COCHRANE.

*7. "Protection of Iron with Paint against Atmospheric Corrosion." By Dr. J. N. FRIEND.

8. "The Casting of Steel in Ingot and other Moulds." By J. E. FLETCHER.
9. "Economic Value of the Jurassic Iron Ores of Great Britain." By Dr. F. H. HATCH.
10. "Notes on a Telescopic Focussing Apparatus for Photomicrography." By A. F. HALLIMOND.
11. "Case-Hardening Practice." By D. HANSON and J. E. HURST.
12. "Use of Bosh Tuyeres in the Blowing of Basic Pig Iron." By J. S. HOLLINGS.
13. "On Magnetic Analysis as a means of Studying the Structure of Iron Alloys." By K. HONDA.
14. "Prevention of Growth in Grey Cast Iron." By J. E. HURST.
15. "Fuel Economy in Blast-Furnaces." By T. C. Hutchinson.
16. "Standardisation of Tests for Refractory Materials." By COSMO JOHNS.
17. "Steel Ingot Defects." By J. N. KILBY.
18. "Effect of Mass on Heat Treatment." By E. F. LAW.
19. "Economy in Gas Cleaning." By A. LENNOX LEIGH.
20. "Manufacture of Portland Cement from Blast-Furnace Slag." By E. H. LEWIS.
21. "Non-metallic Inclusions in Steel." By A. MCCANCE.
22. "The Utilisation of Waste Heat from Open-Hearth Furnaces for the Generation of Steam." By T. B. MACKENZIE.
23. "Influence of Elements on Tenacity of Basic Steel." By A. MCWILLIAM.

24. "Technical Aspects of the Establishment of the Heavy Steel Industry in India with Results of some Researches connected therewith." By A. MACWILLIAM.
25. "A Cause of Brittleness in Mild Steel Boiler Plates." By Dr. W. ROSENHAIN and D. HANSON.
26. "Determination of Cobalt and Nickel in Cobalt Steel." By W. R. SCHOELLER and A. R. POWELL.
27. "Hardness Testing: Relation between Ball Hardness and Scleroscope Hardness." By A. F. SHORE.
28. "Blast-Furnace Bears." By Dr. J. E. STEAD.
29. "Iron, Carbon, and Phosphorus." By Dr. J. E. STEAD.
30. "Notes on Inclusions in Steel and Ferrite Lines." By Dr. J. E. STEAD.
31. "Production of Sound Steel by Lateral Compression of the Top Portion of the Ingot." By B. TALBOT.
32. "Phosphorus in Malleable Cast Iron." By J. H. TENG.
*33. "Effect of Cold Working on the Elastic Properties of Steel." By J. A. VAN DEN BROEK.
34. "Effect of Cold Work on the Divorce of Pearlite." By J. H. WHITELEY.
35. "Notes on the Warping of Steel through Repeated Quenching." By J. H. WHITELEY.

The contributions by Mr. J. A. Van den Broek and Dr. Newton Friend, marked *, were presented as reports of work carried out in connection with the Carnegie Scholarship Fund, and have been published in Volume IX. of the Carnegie Scholarship Memoirs for 1918. In addition to the foregoing the following Carnegie Scholarship Reports were also received, and have been published in the volume of the memoirs referred to:

"An Investigation on the Wearing and Anti-frictional Qualities of Cast Iron." By J. E. HURST (Acton).

"The Chemical Detection of Strain in Iron and Steel by their reaction with Nitric Acid." By J. H. WHITELEY and A. F. HALLIMOND (Stockton-on-Tees).

BESSEMER MEDAL.

The Bessemer Gold Medal for the year 1918 was awarded to the retiring President, Sir William Beardmore, Bart., in recognition of his eminent services in engineering and metallurgy.

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ANDREW CARNEGIE RESEARCH FUND.

A volume of the Carnegie Research Memoirs (Vol. IX.) received during 1918 has been published. A reference to its contents has already been made above.

Four new applications for grants were received during the year, and awards were made to the following:

S. L. HOYT (Minneapolis, U.S.A.), £100 for an investigation on the foreign inclusions in steel, their occurrence and identification.

J. N. **Kilby** (Sheffield), £100 to carry out an investigation on the basic open-hearth process of steel-making, including its chemistry.

G. **Patchin** (London), £100 to carry out research upon semi-steel and its heat treatment.

J. A. **Van Den Broek** (Ann Arbor, Mich., U.S.A.), £100 to enable him to continue his studies upon the effect of cold working on the elastic properties of steel.

Publications.

Two volumes of the Journal, a volume of Carnegie Scholarship Memoirs, and a List of Members have been published during the year, aggregating a total of 1458 pages of text and 79 plates, besides numerous other illustrations. The greatly increased cost of all printing and the scarcity of paper led the Council to decide temporarily to abandon the comparatively expensive cloth bindings hitherto adopted, and to issue the Journal in stiff cartridge paper covers instead. Members desirous of having their copies of the Journal uniform with the bound copies previously issued can, however, have their copies bound for the sum of five shillings per annum, or can be supplied with covers for binding at a charge of a shilling each.

The usual abstracts of all the principal articles and memoirs relating to the technology of iron and steel, published in the Transactions of kindred Institutions and Societies, and in the technical press of this and other countries, together with detailed references thereto, have been compiled and published in the Notes on Home and Foreign Iron and Steel Industries, forming Section II. of each volume of the Journal. In the collection and compilation of these abstracts, over 300 different periodicals, as well as the Transactions of numerous Institutions, have been systematically searched, and reference to the information contained therein has thus been indexed for immediate reference. An index to the technical and scientific literature on iron and steel and kindred subjects is kept up to date in the Library of the Institute, which facilitates the supply of information in response to any inquiries on the part of the members.

Committee Work.

During the year several of the Technical Committees appointed by the Council in 1917 held meetings. An interim report on Blast-Furnace Practice was presented by Committee No. 2 at the May

Meeting and discussed. The points dealt with in this report, which was published in the Journal (No. I., 1918), were, the effect of the mechanical and chemical conditions of raw material on the furnace working, and the influence of the dimensions of the bell in relation to the stock line. The use of double bells, the size and quality of firebricks, and the use of waste gas for calcining iron-stone were also reported upon, and several members of the Committee presented papers dealing with various phases of blast-furnace practice at the meeting in question and at the Autumn Meeting.

Committee No. 3 has appointed a Sub-Committee on Open-Hearth Furnace Design, and has held two meetings. It has also been instrumental in securing several very valuable papers on steelworks practice for reading at the meetings.

The Sub-Committee on Standard Steels appointed by Committee No. 5 has also held three meetings, and has set up an organisation whereby steelworks and their laboratories, the various universities or equivalent institutions, as well as commercial laboratories and analysts in various centres of the steel industry, will collaborate with the National Physical Laboratory in the preparation of the standardised samples. It is hoped that the various steelworks will generously provide the necessary ingots or bars for the production of the samples, and will allow their chemists and laboratories to collaborate for this purpose, free of charge. Definite promises to this effect have already been received from a number of important firms.

In order to carry out efficiently the work at various centres, a number of "District Authorities" have been constituted, viz.: in London, Sheffield, Middlesbrough, Birmingham, Glasgow, and South Wales. Universities, or equivalent institutions, works and commercial laboratories in each district are represented on these bodies.

The first work of the Committee will be the preparation of standards for sulphur, phosphorus, and carbon, six steels with the following approximate proportions of the elements being under selection for the preparation of the standards:

Sulphur	0·03 and 0·07 per cent. respectively
Phosphorus	0·03 and 0·07 " "
Carbon (acid open-hearth)	0·7 per cent.
Carbon (basic open-hearth)	0·1 "

Details of the procedure for selecting the ingots and for the preparation of samples for analysis and their standardisation have been drawn up and circulated to the District Authorities.

LIBRARY AND READING ROOM.

The attendance of members in the Reading Room of the Institute has been well up to the average of previous years, and the facilities for borrowing books from the library continue to be much appreciated. The additions made to the collection of books include the following donations from authors, publishers, and others to whom the Council take this opportunity of extending their thanks: "Memoir on British Resources of Sands suitable for Glass Making," by P. G. H. Boswell; "Supplementary Memoir on British Resources of Refractory Sands for Furnace and Foundry Purposes," by the same author; "A Handbook of Briquetting," by G. Franke; "Les Établissements Schneider," "L'Industrie de l'Acier en France," by J. Tribot-Laspière; "Mineral Enterprise in China," by W. F. Collins; "Bibliography of the Mineral Wealth and Geology of China from 1912 to 1917," by Chung Tu Wang; "Ingots and Ingot Moulds," by A. W. and H. Brearley; and "The Chemical Analysis of Iron," by A. A. Blair (8th edition).

While every endeavour is made to keep the Library of the Institute up to date so far as its financial resources admit, the Council wish once again to urge upon authors the claims of the Institute to presentation copies of works on iron, steel, and its allied industries. Such copies will be most gratefully received and promptly acknowledged. Amongst the books that have been acquired by purchase for the library are: "Modern Coking Practice," by J. E. Christopher and T. H Byrom (vol. i. Raw Materials and Coke; vol. ii. By-Products); "Conditions des Essais et de Reception des Métaux," by G. Charpy; "Metallurgy of the Non-Ferrous Metals," by W. Gowland (2nd edition); "Methods of Measuring Temperatures," by E. Griffiths; "Dyeing with Coal Tar Dyestuffs," by C. M. Whittaker; "Electrolytic and Electrothermal Processes," by E. K. Rideal; "Principles, Operations, and Products of the Blast-Furnace," by J. E. Johnson, jun.; "The Principles of Economic Geology," by W. H. Emmons; "Technical Handbook of Oils, Fats, and Waxes," by J. Fryer and E. Weston (vol. i. Chemical and General); "Hardening and Tempering of Steel," by F. Reiser, "Coal, its Scientific Uses," by W. A. Bone; "The Principles of Iron Founding," by R. Moldenke; "Practical Pyrometry," by E. S. Ferry, G. A. Shook, and J. R. Collins; "Les fours électriques de laboratoire," by Jean Escard; "Trempe, Recuit et Cémentation," by L. Grenet; "Introduction a l'étude de la Métallurgie," by H. Le Chatelier; "La Lime," by C. Fremont, "Essai d'une theorie des fours à flammes basée sur les lois d'Hydraulique," by W. E. Groume-Grijmailo.

APPOINTMENT OF REPRESENTATIVES.

The President continues to represent the Institute on the General Committee of the Royal Society for administering the Government Grant for Scientific Investigations. Sir Hugh Bell, Bart., and Sir W. H. Ellis, G.B.E., represented the Institute on the Board of the National Physical Laboratory, and Sir Hugh Bell also continues to act as representative on the Board of Governors of the Imperial College of Science and Technology. On the British Engineering Standards Association the Institute is represented by Dr. Arthur Cooper, Mr. G. Ainsworth, and Mr. Illtyd Williams, and Mr. Charles Dorman continues to serve on the Engineering Standards Sub-Committee for the Standardisation of Galvanised Sheets, and Mr. R. E. E. Spencer on the Sub-Committee for Special Steels for Motor-Car Construction. Mr. H. J. Yates has been appointed to serve on the Sub-Committee for Cast Iron, working under the direction of the Sectional Aircraft Committee. Sir William Beardmore, Bart., and Mr. G. Ainsworth continue to represent the Institute on the Technical Committee of Lloyd's Register of British and Foreign Shipping, and Mr. J. H. S. Dickenson represents the Institute on the Technical Committee of Motor Industries. Sir Hugh Bell and Sir Charles Allen represent the Institute on the Board of Scientific Societies of the Royal Society. Dr. Arthur Cooper was appointed to represent the Institute on the Council of the Engineering Training Organisation. Sir Robert Hadfield has been re-elected as representative of the Institute on the Court of Sheffield University, Mr. W. Peter Rylands serves in the same capacity on the Court of Liverpool University, and Mr. W. R. Lysaght, C.B.E., on the Court of the University of Bristol.

GRANTS TO OTHER ASSOCIATIONS.

As reported last year, the Council voted a sum of £500 as a grant to the British Engineering Standards Association (Engineering Standards Committee) for the purpose of assisting the Association to increase its activities in foreign countries. The grant is payable in three yearly instalments, the second of which, amounting to £166, was paid during 1918.

CHANGES ON THE COUNCIL.

The election of Mr. Eugène Schneider as the new President has already been referred to. Sir Gilbert H. Claughton, Bart., was appointed to the Vice-Presidency, rendered vacant by the accession of Mr. Schneider to the Presidential Chair, and Professor Henry Louis was elected a new Member of Council to fill the seat on the Council vacated by Sir Gilbert Claughton on his accession to the Vice-Presidency. At the Council Meeting of February 7, 1918, it was unanimously resolved that Mr. Alexandre Pourcel (Bessemer Medallist) be elected an Honorary Vice-President of the Institute.

The Vice-Presidents and Members of Council who, in accordance with Bye-law 10, are due to retire in May 1919, whose names were announced at the last Autumn Meeting, are: *Vice-Presidents*—Sir Gilbert H. Claughton, Bart., Mr. Andrew Lamberton, and Mr. Edward Steer. *Members of Council*—Mr. F. W. Harbord, Mr. G. Trasenster, the Marquess of Graham, Mr. Benjamin Talbot, and Mr. Maximilian Mannaberg. No other members having been nominated up to within one month previous to the Annual Meeting of 1919, the retiring members are presented for re-election.

MEMBERS ON SERVICE IN THE FORCES OF THE ALLIED NATIONS.

The following is a list of those members who are known to have been on active service in the War. The list has been made as complete as possible, but there are possibly members, subjects of other allied countries, concerning whom no note has yet been received. In those cases where no alteration in rank has been notified since 1917, the same rank is given as in the list published in that year.

NAME.	TOWN.	RANK.
Ablett, C. Antony, O.B.E.	London	Captain
Aitchison, L.	London	Captain, R.A.F.
Allen, Cecil, D.S.O.	Sheffield	Major
Allen, Sir Charles, V.D.	Sheffield	Colonel
Anderson, J. A.	Newcastle-on-Tyne	
[1] **Arbel, Lucien**	Paris	Lieutenant
Armitage, William J.	Sheffield	Major
[2] **Armstrong, Percy T.**	London	Lieutenant
Arnison, A. B.	Wylde Green, Warwickshire	2nd Lieutenant (R.G.A.)
Aspinall, Sir John A. F.	Liverpool	Lieut.-Colonel
Atkinson, H. Milne.	Manchester	Captain
Badlam, S.	Beaver Falls, U.S.A.	Captain
Bagley, C. H. F.	Stockton-on-Tees	2nd Lieutenant
Bagnall-Wild, R. K.	London	Brig.-General
Balzarotti, G. P.	Milan	Lieutenant
Baraduc-Muller, Louis	Paris	Captain
Bayley, H. Dennis	Nottingham	Lieut.-Colonel
Belaiew, N. T., C.B.	London	Colonel

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[1] Awarded "La Croix de Guerre avec Palme."
[2] Deceased.

NAME.	TOWN.	RANK.
Bell, Maurice L., C.M.G., V.D.	Northallerton	Lieut.-Colonel
Bengough, G. D.	Liverpool	Captain
Beresford-Jones, H.	Chester	Captain
Bixby, G. B.	Ipswich	Lieutenant, R.A.F.
Boden, W.	Matlock	Lieutenant (R.G.A.)
Bowden, Geo. Harland, M.P.	St. Albans, Herts.	Lieut.-Colonel
Boyd, Archibald J.	London	Lieutenant
Brainerd, H. S.	Munhall, U.S.A.	Lieutenant
[1] **Breuil, Pierre**	Nogent-sur-Marne, France	2nd Lieutenant of Artillery
Brightmore, F. S.	Sheffield	Captain
Browne, S.	Ebbw Vale	Captain
Bull, R. A.	Pittsburgh	Captain
Burnett, G. R.	Sheffield	Private
Burnyeat, R. W.	Workington	Captain
Butler, A. I. R.	Newport, Mon.	Major (Commanding)
[2] **Butler, Basil H., M.C.**	Leeds	Major
Butler, Hubert Oswald	Newport, Mon.	Captain
Campbell, W.	New York	Lieut.-Commander
Cantley, T.	New Glasgow, Nova Scotia	Colonel
Carnegie, David	Beckenham Hill, Kent	Colonel
[3] **Cheesewright, W. F., D.S.O.**	London	Lieut.-Colonel
[3] **Christie, Malcolm G., D.S.O. M.C.**	Leeds	Lieut.-Colonel
Clark, E. Kitson	Leeds	Lieut.-Colonel
Cleland, W. L.	Newcastle, N.S.W.	
Clough, T. Carter	Sheffield	Major
Coe, Henry I.	Swansea	Lieutenant
Colver, Dr. E. de Wykersley Swyft	Sheffield	Captain
Colville, D.	Glengarnock	Captain
Connolly, J.	Birmingham	Lieutenant
Coombe, L. Jackson	Sheffield	Major
[4] **Cooper, Douglas Ludlow**	Middlesbrough	British Red Cross
Cowan, J. H.	London	Colonel
Crompton, Rookes E. B.	London	Colonel
Crosland, J. C. H.	Mobberley, Cheshire	Lieut.-Colonel
Cushman, A. S.	Washington, D.C.	Lieut.-Colonel
[5] **Darwin, Erasmus**	Middlesbrough	2nd Lieutenant
Davie, Thomas, Jun.	Coatbridge, N.B.	Lieutenant
Davie, W. S.	Glasgow	Major R.E.
Davies, D. Sidney	Gateshead-on-Tyne	
Davies, H. L.	Gowerton, Glam.	Captain
Davis, Frank P.	Nottingham	Captain
Dick, Robert D.	Redcar, Yorks.	Private
Dixon, C.	Sheffield	2nd Lieutenant
Dore, Alan S. W.	London	Lieut.-Colonel, R.A.F.
Dorman, Arthur	Yarm, Yorks.	Major

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[1] Created Chevalier of the Legion of Honour.
[2] Awarded the Military Cross.
[3] Awarded the D.S.O.
[4] Awarded Italian Bronze Medal for Valour.
[5] Killed in action, April 23, 1915.

NAME.	TOWN.	RANK.
Ellison, W. R.	Sheffield	Major
Else, F.	Sheffield	Lieutenant
Else, L. H.	Sheffield	Lieutenant
Else, Stanley Cyril	Sheffield	Lieutenant
Fernihough, H.	Sketty, Glam.	Lieutenant
Field, G. K.	London	Major
Fould, M..	Paris	Captain
Friend, J. N.	Worcester	Captain
Graham, Marquess of	Isle of Arran, Scotland	R.N.V.R. Headquarters, Glasgow
Gray, William Carlaw	Glasgow	Captain
Guillain, Armand	Paris	Lieutenant.
Gwynne, R. H. B.	Bristol	Lieutenant
Hammond, Joseph	Wollaston, Stourbridge	Captain
Hedley, George	Middlesbrough	Major
Henderson, The Hon. E. B. Butler	Stafford	Captain
Hopkinson, Allen H.	Huddersfield	Recruiting Officer
[1] **Hopkinson, Prof. B., F.R.S.**	Cambridge	Major (Camb. Univ. O.T.C.)
Horne, James W.	London	Private.
Ide, M.	Kure Arsenal, Japan	Lieutenant
Ingle-Finch, George	London	2nd Lieutenant
Jackson, G. M.	Chesterfield	General
Jackson, J. Arthur	Calderbridge	Lieut-Colonel
Jamieson, E. A.	Ottawa, Canada	Lieutenant
Jenkins, Robert William	Rotherham	Captain
Jobson, R. H. T.	Newcastle-on-Tyne	Major
Johnson, Herbert Alfred	Manchester	Lieut.-Colonel (Commanding)
Johnson, Walter L.	Middlesbrough	Lieut.-Colonel
Kitson, The Hon. R. D., M.C.	Leeds	Captain
Koucharjevsky, S. L.	Bordeaux	Lieutenant
[2] **Labrousse, C. J.**	Paris	Captain (Commanding)
Laycock, W. E.	Sheffield	Lieutenant
Lees, John	W. Bromwich	Major
Lewis, R. A.	Ebbw Vale, Mon.	Captain
Lloyd, D. C.	Tettenhall	Captain
Lloyd, D. W. Edison	Merthyr Tydfil	Engineer
[3] **Longden, A. H.**	Plumtree, Notts.	Captain
[4] **Lusk, J.**	Motherwell	Captain and Adjutant
McBean, Alex., V.D.	Wolverhampton	Colonel
[5] **M'Court, Cyril D.**	London	2nd Lieutenant
McNeill, Hugh Colley	Bombay, India	Farrier Sergeant-Major
McWilliam, Dr. A.	Glasgow	Captain (Commanding)
[6] **Marsh, John L.**	Sheffield	Captain
Merrett, Prof. W. H.	Wallington, Surrey	Major
Messler, E. L.	Pittsburgh, U.S.A.	Captain

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[1] Killed while flying near London, August 27, 1918.
[2] Awarded La Croix de Guerre. Killed in action October 7, 1916.
[3] Died in hospital, March 2, 1919.
[4] Awarded Cross of Legion of Honour. Died of wounds in France, December 29, 1915.
[5] Killed in action, October 8, 1916.
[6] Killed in action, October 16, 1915.

NAME.	TOWN.	RANK.
Monks, Austen J.	Appleton, Cheshire	Captain
Monks, F. Remund.	Appleton, Cheshire	Major (Commanding)
Morden, S. H.	London	Captain R.E.
Morgan, K. P. Vaughan	London	Captain
Morgan, Penry Vaughan	London	Lieutenant
Mortimer, J. E.	London	Engineer Captain.
Needham, Joseph G., D.S.O.	Manchester	Lieut.-Colonel
Nicholson, F., M.C.	London	Captain
Nicou, Paul-René	Paris	Captain
O'Neill, H.	Sheffield	Pioneer
[1] Paton, J. H.	Birmingham	Lieutenant
Pennymore, P. G., D.S.O.	Stourbridge	Lieut.-Colonel
Petherick, John	London	Major
Phillips, George, J.P.	Oxford	Staff Major-General
Pollen, Francis H.	London	Commander
Pollen, Stephen H.	London	Lieut.-Colonel
Randall, Charles R. J.	Barrow-in-Furness	Eng. Lieut.-Commander R.N., Squadron Commander (E.) R.N.A.S.
Rees, W. D.	London	Colonel (Commanding)
Reichwald, V. B.	London	Quartermaster-Sergeant
Richards, John A.	London	Engineer Captain
Rider, B.	Rotherham	2nd Lieutenant
[2] Robin, Felix.	Paris	Lieutenant
Robinson, P. S.	Rochdale	2nd Lieutenant
[3] Rogerson, W. E.	Darlington	Captain
Rosevere, G. R.	Wolverhampton	Lieutenant
Ross, A. A.	London	Major, R.A.F.
Routledge, W.	Marton-in-Cleveland	Captain
Russell, G. A. V.	Sheffield	Lieutenant, R.E.
Sankey, H. Riall, C.B.	London	Staff Captain
Savage, Geoffrey H.	London	Captain
[4] Schneider, Henri P.	Paris	Lieut. of Cavalry, attached French Flying Corps
[5] Schneider, Jean	Paris.	Lieut., attached French Flying Corps
[6] Schneider, Charles.	Paris	2nd Lieutenant
Schoenfuss, F. H.	Washington, D.C.	Captain
Seaman, Wilfred A., M.C.	Sheffield	Major, R.E.
Selby-Bigge, D. L.	Glasgow	Lieut.-Colonel
[7] Shirley, F. L.	Briton Ferry	Private
[8] Sidney, Leicester P., Jun.	London	Flight Lieutenant
Skelton, J. H.	London	
Smith, J. Cruickshank	London	Lieutenant
Smith, Percy W.	Solihull	Captain
Somers, Frank	Birmingham	Captain

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[1] Died March 1919.
[2] Killed in action.
[3] Died at Bullswater Camp, Woking, November 13, 1914.
[4] Killed in action, February 23, 1918.
[5] Received Order of the Chevalier of the Legion of Honour.
[6] Awarded the Croix de Guerre.
[7] Killed in action, August 1, 1918.
[8] Killed in action, October 2, 1917.

NAME.	TOWN.	RANK.
Speakman, E. M.	London	Lieutenant
Steel, H., Jun.	Sheffield	Captain
Stewart, V. Beardmore, O.B.E.	Glasgow	Captain
Storey, Charles B. C.	Chirk, Denbighshire	Lieutenant
Struthers, J. G.	London	Flight Sub-Lieutenant
Taylor, H. J. C.	Sheffield	
Taylor, P.S.	Birmingham	Lieut., R.A.F.
Thomas, W. P.	London	Captain
Thomlinson, W.	Seaton Carew	Lieut.-Colonel
Tofts, C. F.	Bombay, India.	Captain
Trubshaw, H. E.	Llanelly	Major
Underwood, R. G.	Thundersley, Essex	Lieutenant
Wadham, Walter F. A.	Dalton-in-Furness	Lieut.-Colonel (Commdg.)
Walker, Edwin	Sheffield	Lieut., R.E.
Webster, F., M.C.	Chester	Captain
Whitehead, Lionel D.	Abergavenny, Mon.	Captain
Wood, E. R., Jun.	Philadelphia, U.S.A.	Captain
Wraith, H. O.	Windermere	Major, R.E.
Wright, J. R.	Blackpill, Glam.	Colonel
Wright, W. Charles	London	Colonel
Wyman, R.	Newport, Mon.	Captain

The following members of the Institute Staff have also served in the Army:

[1] **Arthur Dowd**	Rifleman (K.R.R.C.)
[2] **Richard Elsdon**	Corporal (R. Inniskilling Fusiliers)

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[1] Died at Havre. February 4, 1919.
[2] Severely wounded at Langemarck, August 5, 1917.

THE IRON AND STEEL INSTITUTE.

BALANCE SHEET, DECEMBER 31, 1918.

LIABILITIES.

To Sundry Creditors:—			
Journal Printing and Publishing		£926 6 1	
Journal Postages...		57 2 11	
Library Books and Binding		5 3 7	
Office Rent, &c.		177 10 11	
Stationery and Printing		29 12 3	
Sundry Payments		9 8 8	
			£1,205 4 5
,, Subscriptions in Advance			61 19 0
,, Entrance Fees in Advance			3 14 6
,, Cash Overdrawn			1,743 18 11
,, Carnegie Scholarship Fund:—			
Sundry Creditors—			
Grants due 1917 and 1918	£175 0 0		
Printing, &c. ...	260 5 10		
		£ 435 5 10	
Amount of Fund represented by investments at cost (*per contra*)		21,241 5 6	
Accumulated Surplus Income:—			
As at 1st January 1918	£1,381 1 11		
Add Excess of Income over Expenditure to December 31, 1918	479 13 2		
		1,860 15 1	
			23,537 6 5
,, The Iron and Steel Institute Capital Account:—			
As per last Balance Sheet		£17,419 10 0	
Less Excess of Expenditure over Income for the year		336 5 1	
			17,083 4 11
Namely:—			
Invested Funds, as per last Account	£16,095 4 4		
Invested during year ...	1,350 0 0		
(See *contra*) ...	17,445 4 4		
Amount over invested ...	361 19 5		
	£17,083 4 11		
			£43,635 8 2

ASSETS.

By Subscriptions in arrear, since received			£ 50 8 0
,, Entrance Fees in arrear, since received			4 4 0
,, Interest on Investments accrued due at 31st December 1918, since received			216 14 9
,, Journal Sales, since received			114 13 4
,, Iron, Steel, and Allied Trades Federation, Proportion of Salary, since received			1 0 0
,, Investments on account of Life Compositions, at cost, as per Schedule attached			2,264 17 4
,, Invested Funds of the Institute, at cost, as per Schedule attached			17,445 4 4
,, Telephone Deposit			1 0 0
,, Cash at Bank and in Hand:—			
On Current Account		£ 6 6 0	
Secretary's Balance:—			
At Bank	£246 9 4		
In Hand	3 7 5		
		249 16 9	
		£256 2 9	
Namely:—			
Carnegie Scholarship Fund, in Hand (see below) ...	£3,000 1 8		
Iron and Steel Institute Account, overdrawn (see *contra*)	1,743 18 11		
	£256 2 9		
,, Carnegie Scholarship Fund:—			
Investments at cost, as per Schedule attached (*per contra*)		£21,241 5 6	
Interest on Investments accrued due at 31st December 1918, since received...		295 19 3	
Cash in hand		2,000 1 8	
			23,537 6 5
			£43,635 8 2

ACCOUNT OF INCOME AND EXPENDITURE FOR THE YEAR ENDED DECEMBER 31, 1918.

INCOME.

To Entrance Fees				£ 338	2	0
" Annual Subscriptions (Members)				3932	5	0
" Do. (Associates)				63	0	0
" Life Compositions				220	10	0
" Journal Sales				443	4	1
" Interest on Investments	£587	13	3			
" Income Tax recovered to 31st March 1918 ...	142	12	1			
				730	5	4
" Bessemer Medal Fund:—						
Interest on Investment, *Less* Tax	£11	16	3			
Income Tax recovered to 31st March 1918	4	0	2			
				15	16	5
" Interest on Deposit				30	14	8
" Sundry Receipts				6	0	8
" Sale of Waste Paper				12	5	11
				£5792	4	1
" Balance, being Excess of Expenditure over Income				336	5	1
				£6128	9	2

EXPENDITURE.

By Salaries and Allowance (including Overtime and War Bonus)				£2342	16	0
" Office rent, Cleaning, &c.				705	9	7
" Library Books and Binding				94	1	0
" Office Furniture				1	17	8
" Autumn Meeting				38	9	2
" Annual Meeting				43	9	6
" Journal Publishing Expenses:—						
Printing, &c.	£1797	11	1			
Abstracts	57	7	4			
Translations	22	18	0			
Postage	113	11	6			
				1991	7	11
" Stationery and Printing (including copies of Papers) ...				514	12	11
" Postage and Receipt Stamps				116	11	4
" Insurance				9	11	8
" Telephone				21	10	0
" Travelling Expenses				19	12	5
" Auditor's Fee				21	0	0
" Sundry Payments				41	3	7
" Engineering Standards Committee Guarantee of £500 (3nd Instalment)				166	0	0
" Carnegie Scholarship Fund—Interest on Loan				0	16	5
				£6128	9	2

ANDREW CARNEGIE RESEARCH SCHOLARSHIP FUND.

ACCOUNT OF INCOME AND EXPENDITURE FOR THE YEAR ENDED DECEMBER 31, 1918.

To Interest on Investments:		
£2250 Newcastle-upon-Tyne Electric Supply 4½ per cent. Consolidated First Mortgage Debenture Stock	£ 72 8 10	
£2600 Great Central Railway 4½ per cent. Debenture Stock	83 7 3	
£3000 Great Central Railway 3½ per cent. Second Debenture Stock	74 16 3	
£5000 Great Northern Railway 3 per cent. Debenture Stock	106 17 6	
£5000 Great Eastern Railway 4 per cent. Debenture Stock	142 10 0	
£3000 Caledonian Railway 4 per cent. Debenture Stock	57 11 4	
£2000 North British Railway 3 per cent. Debenture Stock	43 3 6	
£2000 Taff Vale Railway 3 per cent. Debenture Stock	42 15 0	
£2300 India 3½ per cent. Stock	80 10 0	
£2560 4s. India 3 per cent. Stock	76 16 0	
	£780 10 8	
,, Income Tax recovered to 31st March 1918 ...	228 2 11	
		£1008 13 7
,, Iron and Steel Institute Account, Interest on Loan		0 16 5
		£1009 10 0

By Expenditure, viz.:		
Scholarships	£300 0 0	
Printing Memoirs	205 10 2	
Postage of Memoirs	22 1 6	
Salary	52 0 0	
Sundry Payments	0 5 2	
	£579 16 10	
Less Balance of Scholarships for 1917 lapsed	50 0 0	
		529 16 10
,, Balance, being excess of Income over Expenditure		479 13 2
		£1009 10 0

INVESTED FUNDS OF THE INSTITUTE.

£3744 North-Eastern Railway 4 per cent. Preference Stock, cost	£4,207	6	7
£788 North-Eastern Railway 4 per cent. Guaranteed Stock, cost	1,008	14	0
£79 4s. 5d. "B" Annuity, Scinde, Punjaub, and Delhi Railway, expiring 1958, with a Sinking Fund to replace the amount of Stock, cost	1,999	0	7
£50 1s. 8d. "B" Annuity, Great Indian Peninsula Railway, expiring 1948, with a Sinking Fund to replace the amount of Stock, cost	1,267	6	0
£1500 Buenos Ayres Great Southern Railway 4 per cent. Debenture Stock, cost	1,594	12	9
£1000 Commissioners for the Port of Calcutta 4 per cent. Bonds, 1939, cost	982	10	0
£800 Trustees of the Port of Bombay 4 per cent. Bonds, 1939, cost	809	0	0
£750 Great Central Railway 3½ per cent. Second Debenture Stock, cost	659	12	6
£750 Great Northern Railway (Leeds, Bradford, and Halifax) 6 per cent. Guaranteed Stock, cost	1,140	8	6
£511 South-Eastern Railway 3½ per cent. Perpetual Debenture Stock, cost	449	4	5
£3000 War Loan 5 per cent., 1929–1947, cost	2,837	9	0
£400 National War Bonds 5 per cent., 1922, cost	400	0	0
	£17,445	4	4

INVESTMENTS ON ACCOUNT OF LIFE COMPOSITIONS.

£1330 North-Eastern Railway Irredeemable 3 per cent. Debenture Stock, cost	£1,254	17	6
£335 London Electric Railway 4 per cent. Perpetual Debenture Stock, cost	304	14	11
£335 Metropolitan District Railway 4 per cent. Prior Lien Debenture Stock, cost	333	11	2
£335 North British Railway 4½ per cent., 1875, Irredeemable Preference Stock, cost	371	13	9
	£2,264	17	4

ANDREW CARNEGIE RESEARCH SCHOLARSHIP FUND.

£2250 Newcastle-upon-Tyne Electric Supply 4½ per cent. Consolidated First Mortgage Debenture Stock, cost	£2,261	10	0
£2600 Great Central Railway 4½ per cent. Debenture Stock, cost	2,384	5	0
£3000 Great Central Railway 3½ per cent. Second Debenture Stock, cost	2,055	13	6
£5000 Great Northern Railway 3 per cent. Debenture Stock, cost	3,186	16	9
£5000 Great Eastern Railway 4 per cent. Debenture Stock, cost	4,080	16	0
£2000 Caledonian Railway 4 per cent. Debenture Stock, cost	1,693	0	6
£2000 North British Railway 3 per cent. Debenture Stock, cost	1,249	12	6
£2000 Taff Vale Railway 3 per cent. Debenture Stock, cost	1,204	5	3
£2560 4s. India 3 per cent. Stock, cost	1,525	3	3
£2300 India 3½ per cent. Stock, cost	1,600	2	9
	£21,241	5	6

(Signed) ILLTYD WILLIAMS, *Hon. Treasurer.* G. C. LLOYD, *Secretary.*

I have examined the above Balance Sheet and accompanying Income and Expenditure Accounts with the Books and Vouchers of the Institute, and certify them to be correct. I have also verified the Balances at the Bankers and the Securities for the invested Funds as shown above.

(Signed) W. B. KEEN,
Chartered Accountant.

28 QUEEN VICTORIA STREET, LONDON, E.C. 4, 14*th April* 1919.

BESSEMER MEDAL FUND (Trustees: Sir HUGH BELL, Bt., Lord AIREDALE, and FRANCIS SAMUELSON, Esq.).

£534 London and North-Western Railway 3 per cent. Debenture Stock.

THE BELGIAN IRON AND STEEL INDUSTRY DURING THE GERMAN OCCUPATION IN THE GREAT WAR.

By LEON GREINER (Seraing, Belgium).

In July 1914 Belgium was busily devoting herself to her commerce, her industries, and her agricultural pursuits, when suddenly, in the midst of her peaceful activities, came a thunderclap! There were reports of mobilisation; the assembling of arms; joy flies away and anxiety spreads on every countenance. War had broken out!

Hardly had she recovered from her stupefaction when our little country found herself invaded. The declaration of war had not, as yet, even been transmitted by Germany to France; an insolent ultimatum had barely, as yet, been received by our Sovereign, when our frontiers were violated by the foremost of the German cavalry.

On August 4th the forts around Liége were attacked. Their heroic defence lasted more than ten days. They were forced, nevertheless, to yield to the heavy calibre guns which the Germans hastily brought up, although history will record the decisive part which Liége played in the Great War.

Then came the advance, and, while the Allied armies held the Germans in check, there commenced that long period of four and a half years during which our little country was occupied and cut off completely from its King, its Government, and its soldiers.

The German Governor-General who planted his heavy jackboot on Belgium declared himself the representative of the Royal power. In that capacity he legislated, but solely in favour of the invader, and utterly regardless of the rights of private property. The decrees issued by the Governor-General had but a single object: to despoil the land which his troops occupied, as masters; to sow discord between the inhabitants, and to break their spirit by oppressive measures. I will not, in this connection, revert to the acts of barbarism, incendiarism, and massacre of which the enemy army was guilty in Belgium, which will for ever brand it with indelible shame. The whole world knows of the atrocities committed in so many of our Belgian towns, and Vise, Dinant, Andenne, and Louvain constitute so many bloodstains which will for ever adhere to German hands. Nor will I dwell on the innocent victims of the Teuton-soldiery; on the 6000 civilians whose massacre we can no more ever forget than you can the sordid murder of Nurse Cavell and Captain Fryatt. I wish, however, to recall to you more especially that which is hardly less tragic, although it has failed equally to strike the imagination of most foreign peoples—namely, the deportation of our workpeople to Germany.

This act was concealed under the most hypocritical of falsehoods. It was necessary, the Governor stated, in the interests of the country itself, to relieve charity of these useless and undesirable strikers! And thus it was that there came to be interpolated in the history of occupied Belgium this harrowing and most lamentable chapter of the deportation of these alleged "strikers" and of this reversion to the most cruel of the practices of barbarism—slavery! It is in this connection, too, however, that we are able to distinguish the truest sentiments of patriotism, of endurance, of voluntary and courageous sacrifice, even to death itself, of our Belgian workers, who would not work for the enemy. To relate the sufferings, the tortures of these unhappy people would be almost impossible; even to enumerate the martyrology would take too long. The whole world was seized with horror at the accounts of the atrocities which were committed in the name of "charity" and in the "great moral interests of Belgium."

After the hard winter of 1916–17 we saw the return of such of these waifs of humanity as had been able to withstand this ill-treatment and who, famished and utterly worn out, were flung back, without further ado, within the Belgian frontiers. How many of these 125,000 unhappy deportees died in Germany?

What the iron and steel industry of Belgium was before the War you all know; it was only necessary to traverse our little country to appreciate its importance. In 1913 the output of pig iron reached 2,485,000 tons and the production of raw steel was 2,601,000 tons, while the output of finished products at rolling-mills reached a total of 2,162,000 tons.

The invaders have passed over the land and with them their processes of devastation; of this flourishing industry nothing remains but the shadow. The factory chimneys stand out against a sky unclouded by smoke; buildings still stand huddled together with wide gaps between, but only the framework of industry survives, the soul has departed. Our works have been slain!

Blast-furnaces, converters, open-hearth furnaces, rolling-mills, machine tools, have, with very few exceptions, either been carried away or demolished or rendered incapable of resuming operations. How many months must elapse before we hear again the sounds of industrial life? How many years must pass before Belgium can resume her place amongst the big producers of iron and steel?

On August 1, 1914, our country possessed sixty blast-furnaces, of which forty-nine were in blast; their total capacity approximated to 265,000 tons of pig iron per month. On Armistice Day there remained but four intact, representing 6·3 per cent. of the total productive capacity. Within a future which is uncertain, perhaps within a year, twenty-five others, amounting to 44 per cent. of the former capacity, may be put into a fit condition to be blown-in. So much for the blast-furnaces, the sources of all industrial activity in the iron and steel trades.

Most of the rolling-mills have been destroyed by dynamite. Many of the blowing-engines have suffered the same fate. At the works of the Cockerill Company nine rolling-mills have disappeared by these means out of eleven, and only three blowing-engines remain out of twelve. The same conditions obtain at the works of Ougree-Marihaye and at La Providence, and even more desolate are La Louvière Works, which belonged to the big owner, Pol Boël.

Taking it all together, the havoc in the great iron and steel works (taking into consideration only those works which possessed blast-furnaces) is estimated at a purely approximate sum of 210 millions of francs. This amount, based on prices as they existed in 1914, is only the bare cost of the plant destroyed, without taking into consideration any indirect expenses of any kind.

This, then, is the situation. The problems to be solved are numerous: the starting up of the few which have the good fortune to remain; the re-arrangement and restoration of the works. So much for the technical aspects. Side by side with these is the important financial question. Will it not be necessary to sink capital in plant, the cost of which is three times higher now than it was in 1914? How shall we be able, later on, to struggle against competitors whose capital committments are three times less to discharge, or who have been able almost completely to write off the cost of their plant out of the profits they have made during the War? And when industry is re-established, shall not we, who depend on our export trade, find the world's markets occupied by the industries which have developed considerably abroad during the War?

All these problems are grave; the task before Belgium is vague, and we shall not be able to fulfil it without the help of those who, allied with us in the armed struggle, will, I doubt not, be side by side with us in the peace struggle for world-trade, and on whose assistance we must count in the difficult times our industries must yet surmount, after having undergone the harsh German yoke.

What has taken place during these four and a half years of occupation? At the beginning transactions in commerce and operations at works remained perfectly free. For this reason some of the works profited by this period to use up their raw materials and to convert them, for the general benefit of the country, into products of direct utility. Patriotic enthusiasm was intact and unanimous; the moral resistance to the plots of the invader remained invincible, both amongst the workpeople themselves and the leaders of industry. To the stupefaction of the earlier weeks succeeded a period of waiting, a confident waiting for the help of our Allies and for the triumph of justice. The conditions of material existence, the food conditions chiefly, were not insupportable, the privations and restrictions imposed by necessity were resolutely undergone; the whole Belgian people were opposed to the invader, but—it was still possible to breathe.

The industrial output of the country during 1915 was, nevertheless, extremely low. The production of iron was 68,150 tons, that of steel 110,180 tons, and finished rolled products 164,370 tons, which will be seen to be pretty reduced proportions, being only 2·75 per cent. of the pre-war pig iron output, and 4·22 per cent. of the pre-war steel production.

Towards 1916 the Belgian rolling-mills began to use a considerable proportion of crop ends, and the production of the iron and steel works can be given as follows :

	Tons.
Pig iron	127,825
Steel	137,590
Rolled products	223,335

or 5·14 per cent. of the pre-war pig iron production and 5·29 per cent. of the pre-war steel production. But, under what conditions was work carried on! The chief difficulty lay in the scarcity of certain raw materials, and chiefly of manganese. At the Cockerill Works the Germans divided our stock of rich manganese ore into two portions—560 tons which they carried off, and 60 tons which they generously left us. How they were deceived! It was not 60 tons but 1150 tons that we were able to hide from them, at the risk of our liberty, and to transform secretly, partly into spiegel, in the blast-furnace, and partly into ferro-manganese, in the electric furnace. On the other hand, the scarcity of coal for the producers compelled us, as shown by the note on the subject sent by your late President, Mr. Adolphe Greiner, to the May Meeting 1915, to attempt and subsequently to develop the utilisation of pitch as a fuel for the open-hearth furnaces. Special furnaces were constructed with this object, which allowed of our making open-hearth steel of most varied qualities, from sheets for brewery and sugar works vats to tramway sleepers.

The stocks of manganese ore were not, however, inexhaustible, and the War was protracted beyond anything that could have been foreseen. From the end of 1915 and in order to preserve the last few tons of ore for the manufacture of ferro-manganese, we succeeded in recovering the manganese contained in the material found in heaps on the slag tip, slags derived from old acid Bessemer converters. The average analyses of these slags, of which 15,500 tons were recovered by hand picking, was as follows :

	Per Cent.
Iron (about)	10
Manganese	10
Lime	1·50
Silica	55·00

This was the ray of light by which we were enabled to keep things going a bit ; the recovery of the manganese by increasingly efficient means allowed of our manufacturing in the only blast-furnace in activity, and starting with this apparently intractable material: basic pig iron containing 1·5 per cent. of manganese; then open-hearth pig with 4 per cent. of manganese ; then spiegels of varied composition ranging up to 16 per cent. of manganese, and finally, rich spiegel containing up to 30 per cent. of manganese. The latter, whose manufacture involved a burden consisting only of acid slag, lime, and coke (giving rise to a production of 10 tons of slag per ton of coke) was practically free from phosphorus, and replaced ferro-manganese.

Later on this special pig iron became scarce and had to be economised ; tests were made in order to replace a portion of the manganese additions by carbide of calcium made in our electric furnace. These experiments taught us that with a little care it was possible considerably to reduce the manganese additions, in fact we succeeded in working during a campaign of a fortnight by only using 3·25 kilogrammes of metallic manganese per ton of ingots made in the Bessemer converters, besides a little aluminium which was added in the moulds.

Still later, when only the open-hearth furnace was being used —and for a sadly reduced output—and the ferro-silicon had been exhausted, the electric furnace was able, similarly, to undertake the manufacture of this alloy.

We had the satisfaction of using up our very considerable stocks, and in addition large amounts of other materials that it was necessary to save from being requisitioned, namely 1000 tons of rolls, 650 tons of ingot moulds, and 1450 tons of special steels for springs. The barrels of rifles, nickel and chrome steels and other finished products, of the existence of which the Germans knew nothing, were thus sacrificed.

In the end, however, everything was lacking ; raw materials, fuel, refractories, good luck no longer sufficed ; the working shifts became ever shorter and fewer, and finally all activity in our works died down. It was then that the systematic destruction of our plant reached its full development.

The destruction of the Belgian works, under the form of requisitions, was the object of a regular organisation on the part of Germany. Both civilians and the military applied themselves zealously thereto, according to a well-established plan, and special departments were created with this object. Two leading organisations shared in the too facile task: Die Materialbeschaffungstelle and Die Maschinenbeschaffungstelle. The requisition was always based on the terms of one or other of the decrees (there were so many of them!) published by the German Military Government. The military officials of the different organisations promenaded the works to take note of whatever might suit their purposes. The Materialbeschaffungstelle undertook the search for material required directly at the front and supplies intended for military works in the occupied regions. It was this organisation likewise that, by means of the "Rohstoffverwaltung," carried off the high-speed steel for tools and copper of every description. It is needless to dwell on the sordid struggle, the rivalry in cunning, and on the specious conflict which took place between this organised thieving and its victims (who comprised everyone from the largest commercial undertakings down to the smallest individual) each time a decree authorising requisitions was promulgated. Each Belgian, it may be said, sought to preserve, from what was actually no more nor no less than robbery, all or part of the copper in his possession; it may even be added that many succeeded in deceiving their spoilers. How many others, however, had to pay for such attempts by many months' imprisonment!

The Maschinenbeschaffungstelle was only the instrument of a powerful limited company, the Wumba, in Berlin (Waffen und Munitions Beschaffungs Amt), a civil association directly under the control of the Ministry of War. It was to the Wumba that the German works addressed their requests for materials (tools, machines, buildings, overhead travelling cranes, &c.); with the Wumba that they discussed prices, and to the Wumba that they paid for their "purchases." We have seen the directors of large works—colleagues before the War—parading our workshops and steelworks, making their selections as though at a sale, measuring things up calmly and even arguing amongst themselves as to the possession of such and such a machine, just as they would have done had the material really been at their disposition.

The Wumba was the commercial undertaking for which the Maschinenbeschaffungstelle was the supply branch. It was the latter organisation which supplied information as to the existence of our works, which sought for machines corresponding with the specifications as transmitted from Berlin, and which, once the matter was agreed upon, made out the form of requisition, and proceeded to the sequestration of the material. It was, needless to say, well organised! It was often a curious and heartrending spectacle to see the way the Germans proceeded with the demolition and despatch of machinery. Much of our more delicate machinery was already spoiled in the process before ever the trucks upon which they were carelessly thrown, without even a tarpaulin over them, had left the despoiled works, and how many will ever be returned even in fair condition, to say nothing of their being usable? And what a difficult task it will be to recover many of these machines, which their provisional proprietors, resorting to the devices of common "receivers," will probably have "camouflaged" carefully and beyond recognition. To assign a value to the requisitions of this organisation would be difficult. From the commencement it was more particularly machine tools which were its objects. It is said that 60,000 such machines were stolen from Belgium. But if the engineering workshops were the most especially and severely victimised by the Maschinenbeschaffungstelle, the ironworks were not overlooked: cranes, shears, all kinds of appliances, engines of all kinds were removed under its orders, and are, even now, actually being used in the enemy country!

The Germans attempted at the commencement to adopt the method of immediate payment of these requisitions; the refusal to enter into negotiations or to lend a hand to any industrial operations whatever was as unanimous as the refusal to work friendly, and later on even the authorities ceased to endeavour to carry this out. The formula was in many cases extremely attractive—for the buyer: payment of the invoiced price, with a deduction of 10 per cent. in the value per year of service for the depreciation of machinery, to the credit of an account lodged in Germany. It may be asked whether, in the case of an old machine of more than ten years' service being carried off, we should have had to have paid a certain percentage, in recognition of the "service" which was being rendered to us by relieving us of machinery which, despite its age, was still capable of giving valuable service!

An important victim of the Maschinenbeschaffungstelle was the new blast-furnace gas electro-generative group of 10,000 indicated horse-power which the Cockerill Company was about to put in operation in its large central power-house at the moment when war was declared.

On December 1, 1917, and quite suddenly, a Commission, partly civil and partly military, came to take possession of the engines, access to which was forbidden to the staff of the works itself. The dismantling was commenced by an inexperienced gang, who endeavoured to remove the immense collector of the continuous current dynamo blade by blade by means of chisels and of wrenches. Later on a German engineering specialist presided over the work, which lasted for twenty months.

After the motor it was the turn of two overhead travelling cranes of 40 tons capacity, and the hall of 35 metre span which had been specially built to shelter the largest gas-engine in the world. The technical difficulties which had to be surmounted were not little, the driving-shaft with its cranks and armature cross-head alone weighing no less than 130 tons.

The whole of these appliances are actually in course of being set up at the Kraft Ironworks (Abteilung Niederrheinische Huette at Duisburg). I say advisedly in course of being set up, for although the Armistice has been signed for the past six months it would appear that the work is with strange inconsistency still continuing.

The German demolishers put the period of their stay in our works to profit. They used the interior of the huge columns and the girders of the overhead cranes as hiding-places for supplies of the most varying description, introduced into Germany by fraud and stolen from goodness only knows where—ham, brawn, antimony, lead, butter, bottles of wine, copper and high-speed steel, keeping one another company behind the shelter of the steel plates, which were carefully riveted up afresh after the introduction of their compromising contents. A single girder from a workshop 30 metres in height, and intended for the hardening of big guns, had concealed in its interior 700 bottles of wine and 1000 kilogrammes of white metal. The demolitions in Belgium were thus serving a double purpose. Everyone in the industrial world knows by now of the crimes committed by these systematic organisations for destruction and of the means employed to secure raw materials for the works beyond the Rhine; the savage and complete destruction of our works will long remain in our memories, and many visitors to our ravaged country have been able to see our blast-furnaces ransacked and demolished; our powerful motors reduced to fragments, nothing remaining of them but their shorn and twisted foundation bolts; our workshops destroyed; our rolling-mills, with only their sites remaining, covered with a chaotic collection of debris, a mass of twisted scrap and demolished machinery. When it is remembered that this work of destruction was carried out by metallurgists like ourselves, executed coldly under the orders of engineers and Professors of Universities who knew, better perhaps than anyone else, the destruction they were accomplishing, when we contemplate these accumulated ruins, despite our constant and continuous experience during those fifty-one long months of warfare, one feels stupefied at beholding this magnificent testimonial to German "Kultur." The facts demonstrate conclusively that if the recovery of raw material was the avowed object of the organisation this object was none the less often only a pretext. Why should the most vital parts of our plant have been selected for destruction? Why should not, for instance, a single plant have been destroyed entirely for the recovery of the maximum of its materials instead of simply being mutilated and stripped of whatever was easiest to remove? Why undertake the work of devastation throughout every corner of the works simultaneously? Why were the thousands of tons of loose machinery, stores of scrap, not only distributed over the whole country but found in the works themselves, spared in favour of reducing to scrap motors and power-houses, blowing-engines and rolling-mills, the demolition of which was ten times as costly and difficult, or the destruction of a blast-furnace or a reheating furnace whose frameworks represent but an insignificant proportion of material and value as compared with the cost of the furnace itself?

It is therefore perfectly certain that one of the chief objects pursued was to suppress future embarrassing competition, to disable for a long period to come a rival whose energy was dreaded, and to create a market for German enterprise which the Germans imagined they would be allowed to occupy after the War !

I have little more to add : we have now happily emerged from this nightmare, disabled and injured in the struggle, but hopeful and proud of the victory. We have nothing to blush for before the rest of Europe. At the cost of great sacrifice we have shown ourselves worthy of our great Allies, and we await, like them, that era of peace, of fruitful labour and of closer communion which may lead to the recovery of our prosperous past.

DISCUSSION.

The **President**, in proposing a hearty vote of thanks to Mr. Greiner, said he felt very sorry that the members had had to hear of such horrors and atrocities, which it was a shame to mankind should have been committed. He hoped that full knowledge of those deeds would reach the Peace Conference, and that the peace all were awaiting would be an enduring peace.

Dr. A. **Cooper**, Past-President, remarked that as President in 1913 he had participated in the visit of the Institute to Belgium, when he had been much struck, as he believed all the members had been, with the splendid work which was being carried on in that country, which was really a hive of industry. He had been much touched by the description of the havoc that had been wrought, and he was sure all members of the Institute who had taken part in that visit would join with him in expressing their deep sympathy with the Belgians in the terrible time they had undergone. As metallurgists the members regarded it as a wonderful thing to produce a spiegel containing 30 per cent. of manganese from a slag containing 55 per cent. of silica. That alone was amongst many others a feat which deserved the highest congratulations and appreciation. He thanked Mr. Greiner for his very able paper and for his description of what had happened to Belgian plants and machinery during the German occupation.

Mr. F. W. **Harbord**, C.B.E., Member of Council, stated he had recently been in Belgium, and had had the opportunity of visiting the Seraing works, and two or three other works in the district. It was only when one saw the deliberate way in which those works had been destroyed that one could realise fully the terrible sufferings of our Belgian allies. The destruction had in many cases been most deliberate. In most of the works which relied on power from their blast-furnaces, the engines had been taken away. The mills at the Seraing and at other works had been deliberately cut out at the foundations, and in many cases the bolts bent over and left in. It would be necessary to start *de novo* in many cases. The most serious part of the matter, far more serious than the actual taking away of plant, was the loss of business, and he hoped it might be possible in the Peace negotiations to ensure that not only would that machinery be replaced, but that during the time of that replacement the Germans should supply to the Belgians material of the required sections to enable them to maintain their connection while their works were being restored. How far that might be possible he did not know, but something of the sort was due, because no compensation and no restoration of the works could really make up for the terrible damage which had been done, and the immense losses, direct and indirect, which Belgium had suffered in various ways.

Mr. Richard Mather (London) said he had visited the Continent as a member of a Commission sent over by the Government about three weeks earlier, consisting of Dr. Hatch, Mr. Ennis, Mr. Henderson, and himself. After inspecting some of the German steelworks they came back through, and visited works in Luxembourg, Belgium, and Northern France, and were shown the Cockerill works, among others. He was not surprised at the feeling which Mr. Greiner had shown in describing the damage done, the extent of which was appalling. It was not as though one or two works in a single district had been demolished. Every works had been completely put out of action, at any rate for the time being. The estimates contained in the paper were really quite sanguine. The Belgians and the people in the North of France would be very fortunate indeed if they succeeded in getting anything like 25 per cent. of their output of finished steel within another twelve months from the present date. The handicap put on Belgian industry was most serious. No amount of money, and no amount of recovery either of the original Belgian machinery or of corresponding machinery belonging to the Germans which could possibly be transferred, would completely indemnify the Belgians or the firms in the North of France for the damage which had been done to them. It was the unanimous feeling of the members of the Commission that it was the duty of American and British iron and steel works and engineering firms to do whatever lay within their power to help the Belgians by giving them priority of delivery and every other assistance so that they might restore their plant. On behalf of the Commission he wished to emphasise to the members of the Institute the completeness of the damage which had been done, the difficulty of the task the Belgians and French had before them, and how necessary it was that whatever help could be given from Great Britain should be given. In many cases the work of reconstruction would be far more difficult than the building of new works. There were concrete foundations cumbering the ground which would have to be cleared away, and to begin completely afresh would in many cases be simplicity itself compared with the difficulty of removing the debris and the re-erection of the works on the present sites—to which in many cases there were, however, no practicable alternatives.

USE OF PULVERISED COAL, WITH SPECIAL REFERENCE TO ITS APPLICATION IN METALLURGY.

By L. C. HARVEY (London).

A REPORT on the whole subject of the preparation and application of pulverised coal has recently been submitted by the author to the Director of Fuel Research. This report embodies the results of investigations carried out in America, and contains a general résumé of the advantages claimed for the use of solid carbonaceous fuels in pulverised form. The report deals chiefly with the application of pulverised fuel to steam raising, the generation of motive power, and as a source of heat in metallurgical works. The various types of fuels suitable for use in pulverised form are considered, and installations which have been at work for some years in America are described, and particulars are given of the capital cost of the plants, of the working costs and methods of operations.

The following paper is intended to form a supplement to the information contained in the above-mentioned publication, which is referred to hereafter as the "Report." It cannot be denied that remarkable progress in the use of coal in powdered form has been made in America during the past five or six years. The reason that this method has not received in this country the attention which it merits is undoubtedly due to the war and to the difficulties and delays attendant upon the introduction of new systems, radically affecting works operations.

In view of the many and varied valuable by-products derivable from coal which can only be reclaimed by means of distillation, it might be suggested on first consideration that any progress in the direction of economising fuel resources should take the form of preventing consumption of any coal in the raw state. Whenever it becomes an accomplished fact that all industries requiring power or heat can be supplied with cheap electric energy or gas from the super-power stations now proposed, where the coal used will be subjected to distillation, it will be time enough to prohibit the direct combustion of coal. Possibly pulverised fuel will itself play an important part in promoting the universal distillation of coal by providing a ready means for the disposal of the resulting by-product coke. Provided that 12 to 15 per cent. of volatile matter is left in the coke, such fuel can be efficiently burnt in pulverised form.

In the meantime, however, the fact that 12 million tons of coal per annum are pulverised in America affords sufficient evidence of the immediate economy which might be secured by the use of powdered fuel, and what applies to America will apply also, and in greater measure, to this country.

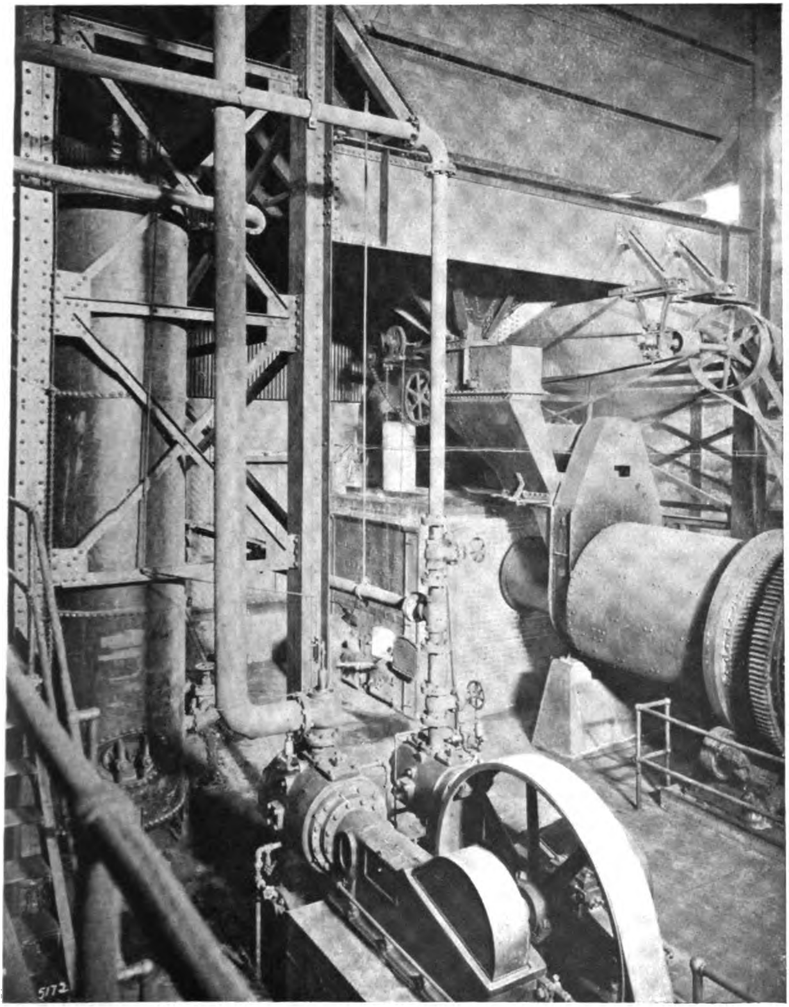
With every increase in rate of wages, prices for materials, fuel, railway transportation, shipping freights, and cost of living will be increased. Water-borne fuel such as oil, which now stands at a prohibitive price, is not likely to become extensively used in England; we must therefore use the coal, lignite, or peat deposits that we have ready at hand, and to far better advantage than we have done in the past.

A six hours' day at the mines, and a 30 per cent. increase in wages over war rates are estimated to cost the community some £45,000,000 per annum, and will probably represent an all-round rise of at least 5s. per ton in the price of coal for industrial purposes. The wages of transport workers, railway employees—in fact, the wages of all classes—are bound to rise in sympathy, so that coal may cost three and probably four times pre-war prices, and the higher the price of coal the more necessary it becomes to cut down consumption.

Although it is rightly claimed for pulverised fuel that any grade of coal can be used in this manner, it is naturally on the high-priced fuels that the savings effected become of greatest monetary value.

By installing pulverised coal systems the whole of the coal supply is concentrated at one or more central milling stations. All truck lines, sidings, engines, truck lifts, &c., and practically all labour for coal transport throughout the works are dispensed with. A view of the interior of a typical coal mill plant is shown in Plate I.

It can be taken as an outside figure that the drying, grinding,



Interior view of typical pulverized coal mill house showing crushed coal storage bin, dryer and Quigley blowing tanks.

and transportation of 100 tons of pulverised coal will require the attention of not more than four men per shift per twenty-four hours; or, say, twelve men on eight-hour shifts, or twenty-four men on six-hour shifts. The usual American allowance for this output is three men per shift per twenty-four hours; two men in the mill house, and one man on the transport line. At the furnaces it is often possible to do entirely without firemen, as the fuel is applied in the same manner as oil or gas, and the temperature within the furnace is easily regulated by the men carrying out the actual metallurgical operations.

Another important economy consequent upon the use of pulverised coal is the reduction in metal loss or scaling. In one instance in America a total amount of 3·68 tons of steel was saved in this manner per day on a reheating furnace having an output of 168 tons of billets (for rolling), or a saving of over 2 per cent. in actual metal as compared with hand-firing. This was chiefly due to the small amount of excess air used with powdered coal. Also, owing to the ease with which a reducing atmosphere can be maintained, oxidation in annealing furnaces is almost entirely overcome, and the life of annealing boxes is in consequence twice as long as with hand- or gas-firing.

In summing up these general advantages, such as saving in coal, saving in works equipment costs, freeing railway space for other purposes, removal of causes for accidents, considerably reduced labour costs for fuel handling and burning, reduced loss of metal often with a considerably increased output of furnace plant and steam boilers, increased life of refractory brickwork (excepting only open-hearth furnaces), increased life to annealing boxes, it must be admitted that there are great possibilities attaching to this system of burning solid fuels. As a means of using up accumulations of low grade and high ash fuels, such as mine tips, and the exploitation of lignite, peat, and other carbonaceous deposits, pulverisation offers a ready solution.

The accompanying table from the Final Report of the Coal Conservation Committee shows a subdivision of coal consumption for home purposes (see Table I.), and upon the figures given an estimate has been made as to the possible total quantity of fuel that might be used in pulverised form.

That this table is necessarily based upon wide assumptions

TABLE I.

	Actual Consumption, 1903.	Proportion of Total Amount for which Pulverised Coal might be Used.	See Note	Raw Coal. Present Consumption Equivalent.	All-round Reduction by Use of Pulverised Coal.	Net Saving of Coal.	Raw Coal. Reduced Consumption in Pulverised Form.	Cost Figures for Powdered Coal Plant, Conveyor System, Burners, &c.
	Tons.			Tons.	Per Cent.	Tons.	Tons.	
Railways	15,000,000	40–50 per cent.,	A	6,500,000	40	2,400,000	4,100,000	On a basis of £25,000 for mill house building and machinery, transport, equipment, and burning apparatus for 100 tons per 24 hours, the cost of pulverised coal plant for 33,000,000 tons per annum would be (for 300 working days) approximately £27,500,000. Interest (at 6 per cent.). Depreciation (at 10 per cent.) on investment = £4,400,000. Maintenance of mill-house machinery and all equipment on American basis 5 cents per ton in mill, and 5 cents per ton on equipment = £687,500. Labour at 9 men per day on 3 shifts for 100 tons per 24 hours at £3 per week per man and payment on 52 weeks = £1,544,400. Dryer fuel and dusting loss at 5 per cent. on 33,000,000 tons of coal at 30s. per ton = £2,475,000. Power for milling, conveying, and burning at 30 kilowatt-hours per ton overall cost of electric power at ½d. per unit = £2,062,500. Total cost for preparing and burning coal in pulverised form = £11,100,000 (say £11,000,000). Overall cost per ton of coal burned in powdered form = 6s. 8d.
Coasting steamers	2,000,000	not feasible at present	B	...	...	...	...	
Factories	53,000,000	Say 30 per cent.	C	15,900,000	20	3,180,000	12,720,000	
Mines	18,000,000	„ 50 „	D	9,000,000	30	2,700,000	6,300,000	
Iron and steel industries	28,000,000	„ 30 „	E	8,400,000	20	1,680,000	6,720,000	
Other metals and minerals	1,000,000	„ 40 „	F	400,000	20	80,000	320,000	
Brickworks, potteries, glass-works and chemical works	5,000,000	„ 25 „	G	1,250,000	30	375,000	875,000	
Gasworks	15,000,000	...	...	...	...	...	...	
Domestic	32,000,000	„ 10 „	H	3,200,000	50	1,600,000	1,600,000	
		Totals		44,650,000			32,635,000	
		Total annual saving in coal by use in pulverised form				11,615,000		
		Total value of coal saving at 30s. per ton				£17,422,500		
		Cost of pulverising and burning				£11,000,000		
		Net annual saving*				£6,422,500		
		Cost of plant and equipment				£27,500,000		
		*Exclusive economy effected in labour costs, loss of metal, &c., &c.						

A. Making allowance for existing electrified lines.

B. Pulverised coal may eventually be used for coasting steamers, either bunkered in powdered form, pulverised on board, or used in colloidal state with crude oil.

C. Assuming that 75 per cent. of the estimated total consumption is used for steam-raising and heating processes.

D. Assuming that the estimated total consumption is for coal used for power and haulage and does not include coal distributed to miners and used for domestic purposes. Usage of coal for heating and subsidiary purposes at the mines may account for a considerable quantity of this total coal used.

E. Coal in pulverised form could undoubtedly be applied very extensively in the iron and steel industries, leaving out of account blast-furnaces and gas-fired open-hearth melting furnaces.

F. For copper smelting powdered coal has replaced other fuels in the States. It could also be used to advantage in the melting and annealing of brass and other alloys.

G. Powdered coal is very suitable for firing kilns and for glass-melting, especially where hand-fired coal or oil fuel firing are now employed.

H. This would only apply to central heating systems for offices, hotels, and institutions, for which purposes pulverised coal would be delivered daily by a Central Supply Company.

is admitted, but it will perhaps indicate the range of possibilities in this direction, and suggest a relation between capital expenditure and overall operating costs for applying and burning powdered coal in the quantities stated.

In his recent address to the Society of British Gas Industries, Sir Robert Hadfield gives very valuable information as to fuel statistics, heating values and costs, and furnace efficiencies for the various methods of heating. By kind permission the accompanying Table II. has been reproduced from Sir Robert Hadfield's address, and to this has been added an estimate of the quantity and cost of pulverised coal required for melting 1 ton of steel.

Table II.—*Melting* 1 *Ton of Steel.*

	Amount of Fuel or Energy consumed.	B.t.u. in Fuel used.	Cost of Fuel.	Fuel. Total Cost.		Heat Efficiency.	Lost Heat.	Tons of Raw Coal used.
	Tons.			*s.*	*d.*	Per Cent.	Per Cent.	
Crucible Melting.								
Coke . . .	2·50	73,000,000	47s.	117	6	1·4	98·6	3·75
Open-hearth Melting.								
Producer-gas . .	0·30	9,400,000	19s.	5	8	13·5	86·5	0·3
Pulverised coal .	0·20	6,272,000	19s.	3	10	20·2	79·8	0·2
Correcting for coal consumed for preparing and burning at 18 lb. coal per ton steel . .	0·208	6,510,000	19s.	3	11	19·5	80·5	0·208
Electric Melting . .	515 units	1,780,000[1]	0·72d.	30	11	68	32	0·66

[1] 20,000,000 in coal at Power Station, 0·66 ton of coal.

In order to arrive at the relative values for pulverised coal, a fuel containing 14,000 B.t.u. (the basis taken for the producer-gas figures) has been assumed, and with such a fuel value a reduction of 8 to 5 can be made as against producer-gas for medium size open-hearth plants.

A fuel economy bearing this ratio was effected in a steelworks in America when melting steel with Illinois coal of 10,000 B.t.u., and on this basis the quantity of coal required to melt 1 ton of steel; given in Sir Robert Hadfield's table, can be reduced to 0·2 of a ton when powdered coal is used.

When considering the use of electricity for steel melting, the figures for power or heat losses given by Sir Robert Hadfield show that we may start with a coal having a value of 14,000 B.t.u.; of which 4957 B.t.u. are used in the furnace, the balance being dissipated in the following order:

Raw coal value = 14,000 B.t.u.

	Per Cent.		
Overall efficiency of boilers	75	= 10,600	B.t.u. used
Turbine efficiency	80	= 8,480	,,
Generator efficiency	92	= 7,801	,,
Line efficiency	99	= 7,722	,,
Transformer efficiency	98	= 7,365	,,
Conductor efficiency	99	= 7,291	,,
Furnace efficiency (taken from Table II.)	68	= 4,957	,,

4957 B.t.u. is, roughly, 35·4 per cent. of the B.t.u. value of the coal used in the generation of electric power supplied to the furnace, and cost per ton melted is 30s. 11d. On the other hand, powdered coal will show the following overall heat value loss:

Raw coal = 14,000 B.t.u.
Drying process 2 per cent. coal value = 13,720 B.t.u.
Power for crushers, elevators, dryers, mill conveyors, and air-fans at furnaces absorb about 30 kilowatt-hours per ton of fuel burned; that is, 0·04 lb. of coal is used for these purposes per lb. of fuel burned. This reduces the 13,720 B.t.u by 560 B.t.u. = 13,160 B.t.u.

Allowing for furnace efficiency of 20·2 per cent. (taken from Table II.) when burning powdered coal, the heat value of coal actually used in the furnace becomes 2444 B.t.u., or 17·4 per cent. of the original B.t.u. value of the coal. Cost per ton of steel melted = 3s. 11d.

Producer-Gas Firing.

Raw coal, 14,000 B.t.u. at 13·5 per cent. overall efficiency = 1890 B.t.u. used.

Cost per ton of steel melted = 5s. 8d.

It must be remembered that there is no possibility of working waste heat boilers in conjunction with electric melting furnaces, whereas with powdered coal and producer-gas possibly 50 per cent. of the heat passing out of the regenerators can be used for raising steam.

This being so, the heat values for the three systems then bear the following relation (p. 53).

In the metallurgical world it will be chiefly in comparison with producer-gas practice that powdered coal will be considered. In certain cases the advantages of the one will outweigh those of the other.

	Heat Value of Raw Coal.	Ultimate Value of Heat used.	B.t.u.'s used per Cent.
	B.t.u.		
1. Powdered coal furnace . .	14,000	7708	55·0
2. Producer-gas furnace . .	14,000	6731[1]	48·0
3. Electric melting furnace .	14,000	4957	35·4

Each system has its rightful sphere of usefulness, and each has its faults and difficulties.

In the new types of modern mechanically fed gas-producers, such as those of the Morgan Construction Company of Worcester, Mass., in which ash removal ploughs are employed in addition to mechanical feed gear, it is stated that one man can tend a battery of six 10-foot producers. This company claims for their most recent 10-foot producers a duty equal to 3000 lb. of coal gasified per hour, giving gas of 178 B.t.u. as against 1600 to 1700 lb. of the same quality of coal gasified in most of the well-known mechanical producers, making gas of about 145 B.t.u. per cubic foot. This means that one man on an eight-hour shift will tend a "Morgan" producer plant handling 144,000 lb. of coal and at 75 per cent. overall heat value efficiency at the furnace a coal equivalent of 138,000 lb. of coal burned in the furnaces.

In a coal pulverising mill a shift of three men will be required to operate the dryer, mills, and conveying system for an output of 8 tons per hour, or 143,360 lb. per eight-hour shift or 47,786 lb. of coal per man, of which 95 per cent. will be received at the furnace or 45,315 lb. of coal burned in the furnace. Normal practice with ordinary mechanically fed producers is said to be only one-fourth the amount of coal handled per man as compared with the latest types of Morgan producers. If this is so, the coal handled per man per shift will be 35,840 lb. per eight-hour shift on ordinary mechanically fed producers; for hand-fired producers but 10,000 lb. or so.

As against hand-fired producers pulverised coal systems therefore show a very greatly increased tonnage handled per unit of labour, and as against normal mechanically fed producers an increase of 25 per cent. In comparison with hand-fired and handpoked producers, moreover, at least four times the heat equivalent of coal can be delivered to the furnaces per single operator per shift.

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[1] This allows for a producer efficiency of 80 per cent., and a furnace efficiency as for powdered coal, 20·2 per cent., which is a liberal allowance for gas-firing.

A comparison between furnace efficiencies for powdered coal, oil, and producer-gas firing has been made by Mr. C. F. Herrington.[1] No allowance for overall efficiency of the plants was made in these calculations, and if one accepts an overall loss of 5 per cent. in coal for powdered fuel systems and 25 per cent. loss for producer-gas practice, then Mr. Herrington's figures for the net overall efficiencies for the three systems bear the following relation as regards actual fuel efficiency:

Powdered Coal (furnace using preheated air for combustion).

Furnace coal at 60° F.
Steel and furnace heated to 2200° F.
Rise in temperature, 2140° F.
By test, 6·29 lb. of steel heated per pound of coal burned.
Specific heat of steel, 0·117.
0·117 × 2140 = 250 B.t.u. per lb. of steel.
250 B.t.u. × 6·29 = 1572 B.t.u. output.
1 lb. of coal = 14,000 B.t.u. input.
Efficiency = $\frac{1572 \times 100}{14{,}000}$ = 11·3 per cent.; or allowing 95 per cent. overall fuel efficiency = $\frac{1572 \times 100}{14{,}716}$ = 10·7 per cent.

Fuel Oil (same furnace with same rise in temperature and the same charge of work).

Heated 8·68 lb. of steel per pound of oil.
1 lb. of oil = 19,400 B.t.u. input.
250 B.t.u. × 8·68 = 2170 B.t.u. output.
Efficiency = $\frac{2170 \times 100}{19{,}400}$ = 11·3 per cent.

Water Gas (furnace using preheated air for combustion).

1 cubic foot of gas = 300 B.t.u.
Specific heat of wrought iron = 0·113 (Kent).
Temperature rise from 1400° to 2500° = 1100° F.
Furnace charged with 3800 lb. iron.
To raise this iron to that temperature required 14,000 cubic feet of gas.
0·113 × 1100 = 124 B.t.u.
3800 × 124 = 471,200 B.t.u. output.
14,000 × 300 = 4,200,000 B.t.u. input.
Efficiency = $\frac{471{,}200 \times 100}{4{,}200{,}000}$ = 11·2 per cent.; or allowing 75 per cent. overall producer efficiency = $\frac{471{,}200 \times 100}{5{,}600{,}000}$ = 8·4 per cent.

No doubt the outstanding questions of particular interest are those concerning capital cost for pulverising plants of various capacities, the overall operating costs for running these plants and attendant conveying and burning expense, also the relation that such figures bear to the price of coal. The author has endeavoured to set out these various costs in concise form both in tables and in curves, but additional allowance must be made for branch conveying systems, coal bins and burner gear at furnaces, boilers, &c.

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[1] *Engineering News*, December 10, 1914.

Such additional cost may be taken at from 30 per cent. to 50 per cent. for normal works equipment, but may reach 100 per cent. on the cost of mill-house plant when furnaces are small and numerous, or scattered over a large area.

It is of little use to consider estimates as to mill-house cost wherein figures relating to capital outlay or running costs have been cut down to the lowest limits, for these minimum costs are seldom experienced in practice. Ample allowance has therefore been made in each instance to cover all reasonable charges at present-day high prices for material, machinery, buildings, &c., and sufficient allowance has been made for maintenance, interest, depreciation, and labour.

In addition to the bare complement of drying and crushing plant necessary for the daily capacities given a series of columns have been added to cover stand-by plant. The provision of the latter slightly increases the overall running costs, due to interest and depreciation charges on idle machinery.

Table III. shows the number and sizes of dryers and pulverisers required for 5 to 1000 tons of powdered coal per twenty-four hours and for complete mill-house equipments.

Unless extensions in the direction of additional furnace or boiler plant are contemplated, it will not be always sound practice to instal a complete mill equipment for a daily output below, say, 20 tons. On the other hand, it may often be the intention not only to use powdered coal in the one department where initial trials are to be carried out, but to extend the application to other shops in course of time. In such cases it will be advisable to instal the complete mill-house plant, but in order to use powdered coal in small quantities it may often be better policy to purchase self-contained pulverising units such as the "Aero" machine.

It will be seen that capital outlay and running costs for small complete mill-house plants may become out of proportion to the benefits to be realised.

In the table of operating expenses (Table IV.) it has been assumed that for the whole range of capacities even below 20 tons per day complete mill-house equipments will be preferred.

Table V. shows capital costs for small self-contained units of the "Aero" type, and overall running costs on the same basis of calculation as for those accepted for the larger installations. It does not necessarily follow that this course is recommended, for under certain conditions the small self-contained units would be quite unsuitable. The difference between the cost of the small unit and that of complete mill-house equipment appears attractive, but the latter affords flexibility of supply,

TABLE III.—*Mill-House Dryer and Pulveriser Mill Equipment.*

Daily Output in Tons.	Output per Hour in Tons.	No. and Size of Mills.		No. and Size of Dryers.		No. of Men.	No. and Duration of Shifts.	Labour. Hours per Day.
		Running Plant.	Stand-by Plant.	Running Plant.	Stand-by Plant.			
		Inches.	Inches.	Tons.	Tons.		Hours.	
5	1-2	1–24	1–24	1–4	None	2	2–8	32
10	2	1–33	...	,,	,,	2	1–8	16
15	2	1–33	...	,,	,,	2	1–8	16
20	2	1–33	1–33	,,	,,	2	2–8	32
30	2	1–33	1–33	,,	,,	2	2–8	32
40	2	1–33	1–33	,,	,,	2	3–8	48
50	4	1–42	1–42	,,	,,	2	2–8	32
60	4	1–42	1–42	,,	,,	2	2–8	32
70	4	1–42	1–42	,	,,	2	2–8	32
80	4	1–42	1–42	,,	,,	2	3–8	48
90	4	1–42	1–42	,,	,,	2	3–8	48
100	6	3–33	1–33	1–8	,,	3	2–8	48
150	8	2–42	1–42	1–8	1–8	2	3–8	48
200	12	3–42	1–42	1–10	1–10	3	2–8	48
250	12	3–42	1–42	1–14	1–14	3	3–8	72
300	16	4–42	1–42	1–14	1–14	3	3–8	72
350	16	4–42	1–42	1–14	1–14	3	3–8	72
400	20	5–42	1–42	2–10	1–10	4	3–8	96
450	20	5–42	1–42	2–10	1–10	4	3–8	96
500	24	6–42	1–42	2–14	1–14	5	3–8	120
550	24	6–42	1–42	2–14	1–14	5	3–8	120
600	28	7–42	2–42	2–14	1–14	6	3–8	144
650	28	7–42	2–42	2–14	1–14	6	3–8	144
700	32	8–42	2–42	2–14	1–14	6	3–8	144
750	36	9–42	2–42	4–10	1–10	7	3–8	168
800	40	10–42	3–42	4–10	1–10	8	3–8	192
850	40	10–42	3–42	6–10	1–10	8	3–8	192
900	40	5–57	1–57	4–14	1–14	6	3–8	144
950	44	6–57	1–57	4–14	1–14	6	3–8	144
1000	48	6–57	1–57	4–14	1–14	6	3–8	144

whereas a separate Aero unit must be installed for each furnace or kiln.

Table IV. contains figures for labour rated at £3 per week

TABLE IV.—*Capital Outlay and Operating Costs of Mill-House Plants of Various Capacities.*

Daily Output in Tons.	Labour. Cost per Ton.	Power. Cost per Ton.	Dryer Fuel per Ton.	Repairs per Ton.	Without Stand-by Plant.				With Stand-by Plant.			
					Cost of Plant, including Building.	Interest per Ton 6 per Cent.	Depreciation per Ton 10 per Cent.	Total Cost per Ton.	Cost of Plant.	Interest 6 per Cent.	Depreciation 10 per Cent.	Total Cost per Ton.
	s. d.	s. d.	d.	d.	£	s. d.	s. d.	s. d.	£	s. d.	s. d.	s. d.
5	4 2	1 6	5	4	3,500	2 9½	4 8	13 10½	4,250	3 4½	5 7	15 4½
10	2 1	1 3	5	4	6,700	2 8	4 5½	11 2½	6,700	2 8	4 5½	11 2½
15	1 8	1 3	5	4	6,700	1 10	3 0	8 6	6,700	1 10	3 0	8 6
20	1 10½	1 3	5	4	8,650	1 9	2 10½	8 6	9,650	1 11¼	3 3	9 1
30	1 5	1 3	5	4	9,300	1 3	2 1	6 9	10,300	1 4¾	2 3½	7 1
40	1 6½	1 3	5	5	9,300	11	1 7	6 1¼	10,300	1 0¾	1 9	6 5
50	10	1 3	5	4	11,100	10½	1 6	5 2¾	12,700	1 0	1 8½	5 6¾
60	8½	1 3	5	4	11,100	9	1 3	4 8¾	12,700	10¼	1 5	4 11¾
70	7	1 3	5	5	11,100	7½	1 1	4 4¾	12,700	8¾	1 2½	4 7¾
80	9	1 3	5	5	11,100	6½	11	4 3¾	12,700	7¾	1 1	4 6½
90	8½	1 3	5	5	11,100	6	10	4 1¾	12,700	6¾	11	4 3
100	7½	1 3	4¾	5	13,500	6½	11	4 1¾	14,500	7	11¼	4 2¾
150	5	1 3	4¾	5	15,000	4¾	8	3 6¾	18,100	5¼	9¼	3 9¾
200	4	1 3	4¾	4½	18,500	4½	7½	3 4¾	23,600	5½	9¼	3 7¾
250	4¼	1 3	4¾	4½	18,500	3½	6	3 2¾	22,550	4½	7¼	3 4¾
300	4	1 3	4¾	4½	19,100	3	5	3 0¾	23,150	4	6¼	3 2¾
350	3½	1 3	4¾	4½	20,550	2¾	4¼	2 11¼	24,600	3½	5½	3 0¾
400	3½	1 3	4¾	4½	22,500	2¾	4¼	2 9	25,850	3¼	5¼	3 0¼
450	3½	1 3	4¾	4½	24,000	2¾	4¼	2 8½	27 350	3	5	2 11¾
500	4	1 3	4¾	4½	25,600	2½	4¼	2 8¾	29,650	2¾	5	2 11¾
550	3½	1 3	4¾	4½	27,500	2½	4¼	2 8¼	31,550	2¼	4¾	2 10¼
600	3¾	1 3	4¾	4½	29,100	2½	4	2 10¼	34,750	2½	4¼	2 11
650	3½	1 2¼	4¾	4½	30,900	2¼	3¾	2 7	36,550	2½	4¼	2 10¼
700	3¼	1 2	4¾	4½	32,500	2¼	3¾	2 8¼	38,150	2¼	4¼	2 9½
750	3¼	1 2	4¾	4½	34,300	2¼	3½	2 8¼	39,250	2¼	4¼	2 9¼
800	3¼	1 1½	4¾	4½	35,900	2¼	3¼	2 8	42,450	2¼	4½	2 9
850	3¼	1 1	4¼	4½	37,500	2¼	3¼	2 7¼	44,050	2½	4¼	2 8¼
900	2¾	1 0	4	4	39,200	2¼	3¼	2 4½	43,900	2¼	4¼	2 5
950	2¾	1 0	4	4	41,200	2	3¼	2 4	45,900	2	4¼	2 4¾
1000	2¼	1 0	4	4	42,500	2	3½	2 3¾	47,200	2	4	2 4¼

Cost of plant covers normal foundations and erection.

per man, power costs at ¾d. per unit, and ample allowance for power has been included. As a rule it is considered sufficient to allow for power at the rate of 20 kw. hours per ton of coal ground, delivered, and burned, but in order to make sure that all contingencies and power requirements for different systems are covered as far as possible 80 kw. hours have been allowed per ton of coal. Repairs and maintenance costs have been based upon American figures, *i.e.* 5 cents per ton in the mill and 5 cents per ton on conveyor and burner apparatus. Interest and depreciation has been taken at 16 per cent. on capital charges. The total costs for the various daily capacities can therefore be taken as representing reliable if not outside figures.

TABLE V.—*Capital Outlay and Operating Costs of Small Self-contained Units.—" Aero " Pulveriser Plant.*

Daily Output in Tons.	Output per Hour.	Labour Cost per Ton.	Power Cost.	Dryer Fuel.[1]	Repairs per Ton.	Interest 6 per Cent.	Depreciation.	Total Cost.	Labour Hours per Day.	No. and Duration of Shifts.	Cost of Plant.[2]
	Tons.	*s.* *d.*	*s.* *d.*		*d.*	*d.*	*s.* *d.*	*s.* *d.*		Hours.	£
5	½	2 7	2 10½	...	1½	9½	1 4	7 8½	10	2–5	1000
10	¾	1 9½	2 0	...	1¼	6¼	10	5 3	14	2–7	1250
15	1	1 4½	2 0	...	1¼	4¾	8	4 6¾	16	2–8	1500
20	2	8	1 7	...	1½	4¼	8	3 5¼	10	2–5	2000

Screw conveyors to deliver the coal 800 feet from the mill house have been allowed for in the cost of plant.

All the above tabulated figures are incorporated in the curves shown in Fig. 1. The initial and rapid rise in cost of " bare output " and " stand-by " installations for complete mill-house equipments will be noticed, and even more marked than these features are the excessive costs for operation on the small complete plants. The inset curve on Fig. 1 shows the more reasonable figures for the self-contained pulverisers.

From these curves a ready estimate can be made as to when it will pay to use pulverised fuel, but in doing so the very many important advantages and economies introduced by the use of powdered coal must not be overlooked. There is, unfortunately, no possibility of showing on these curves such advantages as reduction in labour, increased output of furnaces, reduced metal loss, better work and better working conditions, &c. &c., all of which collectively will place the whole question of mill-house costs in a very different light.

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[1] No dryer used as a rule with this type of plant.

[2] Bare cost of pulveriser and motor only.

The curves shown in Fig. 2 represents the overall cost for the quantity of pulverised coal required for performing the same work as 1 ton of the same coal hand-fired. Six curves are given for raw coal at 10s., 20s., 30s., 40s., 50s., and 60s. per ton respectively, and intermediate values between two coal price curves can be obtained with sufficient accuracy for making any preliminary estimate for equivalent costs of coal in powdered form.

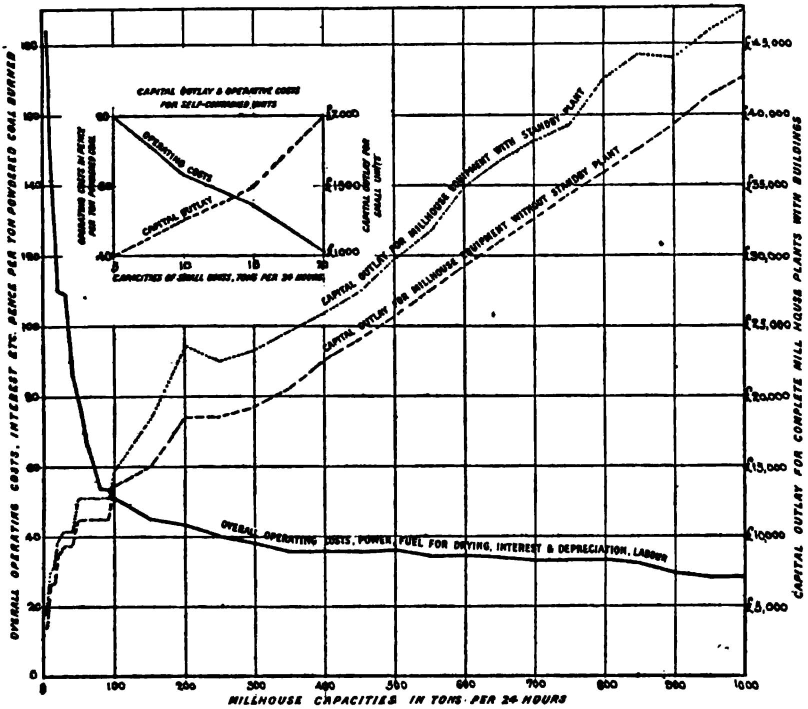

FIG. 1.—Curves showing relation between cost of Mill-House Plants for various capacities per twenty-four hours and overall operating costs.

In order to arrive at the points for constructing the curves, the value of a one-third reduction in coal used, when pulverised coal is applied, has been deducted from the cost of

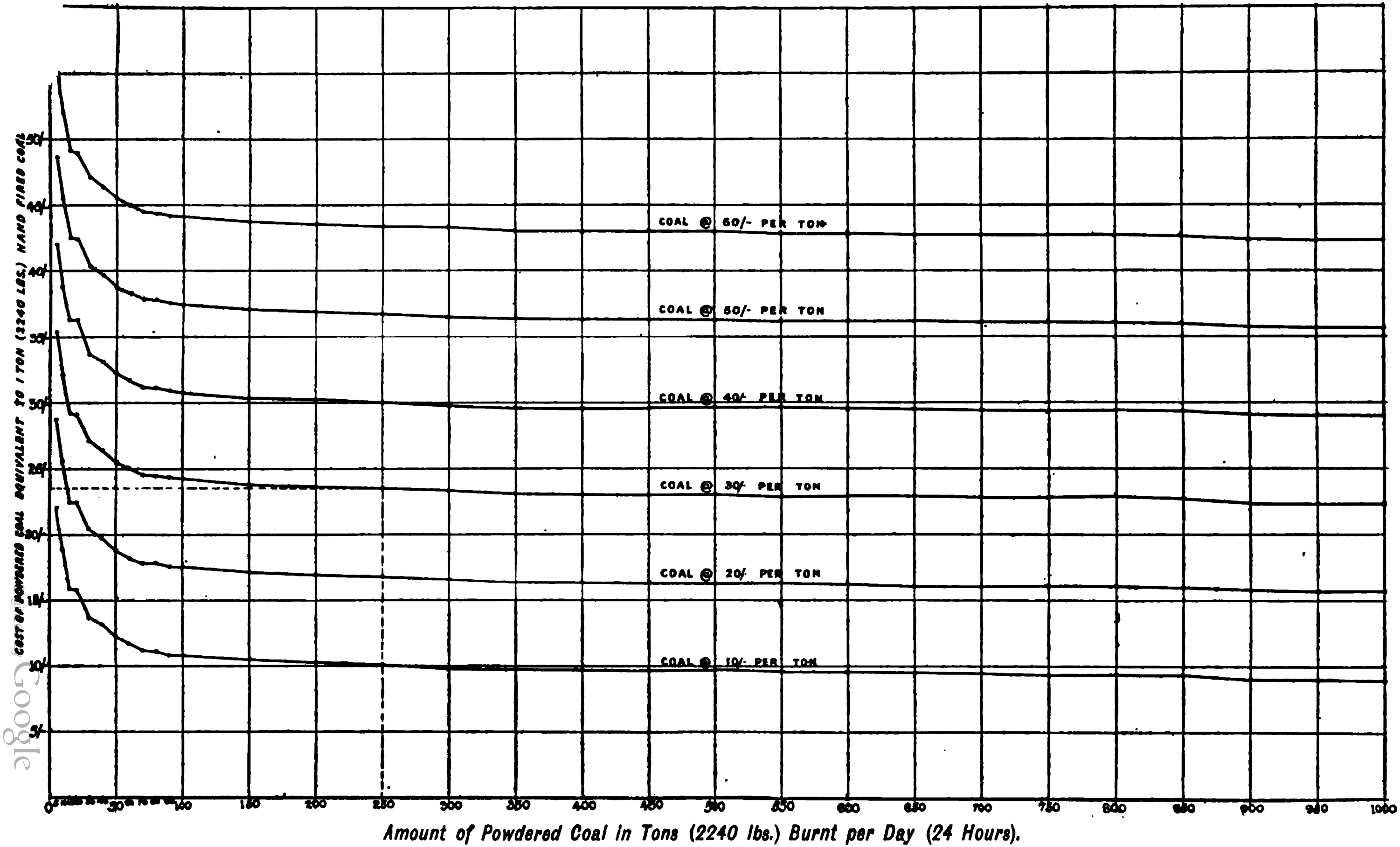

FIG. 2.—Cost of Powdered Coal for performing the same work as 1 ton (2240 lbs.) of hand-fired coal. Assuming 33⅓ per cent. saving in fuel by the use of powdered coal and as an offset against the value of the fuel saving the cost of preparation and burning powdered coal has been added. Costs given for plants of various capacities and for six prices of raw coal.

raw coal. To this result the overall operation cost for the size of plant in question taken from Table IV. has been added in each case.

For instance, with coal at 30s. per ton the value of a one-third

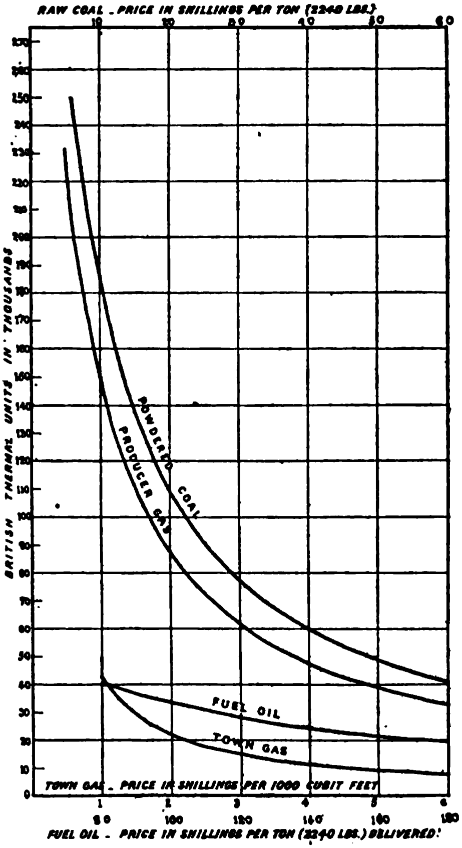

FIG. 3.—The number of B.t.u.'s secured for one penny for commercial fuels at various prices.

reduction in fuel consumption will be 10s., but the overall cost of operation for a powdered coal plant having a capacity of 200 tons per day (see Table IV.) is 3s. 7½d., so that the net value of powdered coal for the purpose of plotting the curve for a 30s. coal will be 23s. 7½d. as against 30s. for hand-firing.

Graph Fig. 8 indicates the relative values of fuels in B.t.u. obtainable for one penny, the fuels considered being powdered coal, producer-gas, fuel oil, and town gas.

In order to arrive at a basis which is as fair as possible for comparison with other fuels, the operating cost for running a powdered-coal plant and the overall expense connected with conveying and burning the fuel at the furnace have been added to the cost of the raw coal.

In the present case this operating cost has been taken at 4s. per ton of coal pulverised, a reasonable figure for a plant capacity of 200 tons per twenty-four hours.

For the same reason, 4s. per ton has been added to the cost of coal gasified in producers of equal total capacity to the powdered coal plant so as to allow for operating costs, interest and depreciation on the producer plant, and it is presupposed that the gas will be burned under natural air-draught conditions.

For powdered coal, fuel oil, and town gas, thermal efficiencies of 100 per cent. have been accepted. Cost of power at ¾d. per unit for air blowers for oil and town gas has been added to the purchase prices of these fuels.

The calorific value of the raw coal has been assumed at 14,000 B.t.u. per lb., that of oil at 19,000 B.t.u., and town gas 550 B.t.u. net per cubic foot.

THE ADVANTAGE OF USING COAL IN POWDERED FORM.

Mr. Joseph Harrington[1] writes: "In the producer there is a succession of losses which reduce the available heat in the gas to a considerable extent, and in the mechanical stoker there are unavoidable losses due to various forms of incomplete combustion. Only in the case of powdered coal is the actual solid fuel both gasified and completely consumed directly within the chamber to be heated. With perfect pulverisation the entire mass is burned in suspension, and in actual practice but a small fraction of 1 per cent. is actually lost in the flue dust or slag pan.

"On account of the fuel being conveyed into the furnace by the very air which is afterwards to be used in its combustion, and on account of the diffusing of the coal throughout the air in a cloudlike formation, there is a possibility of a mixture which can be secured by no other means. Each particle of coal is surrounded by a particle of air, and on account of the extreme fineness of the particles practically instantaneous oxidisation occurs. The result is efficient combustion, and we have to deal only with the effects of the high temperature thereby obtained."

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[1] *American Society of Mechanical Engineers*, October 1916.

It has already been pointed out that higher temperatures than are possible with any other fuel can be maintained in powdered coal-fired melting furnaces, because the quantity of excess air is but 20 per cent., whereas with stoker and hand-firing the excess of air may range from 50 per cent. to 200 per cent., and even 300 per cent.

It will be readily seen that with powdered-coal firing the gases due to combustion of the fuel will be appreciably less than with the usual methods, and consequently the gases will remain in the furnaces for a longer period. The heat transference with pulverised-fuel firing must, therefore, be much more complete than is the case with larger volumes of relatively cool gases which result from hand-firing or even stoker-firing.

Values for heat losses due to excess air supply can be ascertained from Fig. 4. Moisture in fuel, imperfect combustion, carbon in clinker and ash are also causes of considerable losses which are entirely removed by the use of powdered coal.

Heat Loss due to Moisture in Fuel.

Under certain conditions it would probably pay to dry out the moisture contained in coal before using the fuel in the ordinary way on hand-fired grates or mechanical stokers, for, in order to evaporate and drive off 1 lb. of the moisture when the fuel is in the firing chamber, approximately 1250 B.t.u. are wasted in accomplishing this and superheating the resultant steam. This is one of the reasons why dry pulverised fuel burned in a furnace combustion chamber gives such a high heat efficiency.

Lignite generally contains from 20 per cent. to 30 per cent.

of moisture in the raw state, and a certain fuel, having a B.t.u. value of 12,378 per lb. of dry combustible or 10,675 B.t.u. per lb., based on the analysis of the lignite, had only a heat value of 8854 B.t.u. undried. This fuel, dried to 7 per cent. moisture, gave a water evaporation of 8·86 lb. per lb. combustible, and with 1 per cent. moisture 10·90 lb. water evaporation. When fired undried on stokers the water evaporation was but 4 lb.

For every 1 per cent. of moisture in coal it can be taken that the heat value per lb. of fuel will be reduced by 12·5 B.t.u., so that powdered coal which should be dried to this degree will show but a loss of 12·5 B.t.u., whereas a similar coal containing 10 per cent. moisture would show a loss of 125 B.t.u. per lb. of fuel.

Heat Loss due to Imperfect Combustion.

How often does one see flame issuing from the top of a stack in the iron districts, and what a loss of heat this means! Such conditions are presumably brought about by the generation of CO at the fire-grate, which partially burns in contact with oxygen drawn in at furnace cracks and completes its combustion on emergence from the stack.

With powdered coal such uneven firing conditions can be readily prevented over a very wide range of fuel consumption, for complete combustion under all conditions can be made to take place within the actual furnace chamber.

Loss of Coal in Ash and Clinker.

A series of tests were carried out in America to ascertain the value of the carbon lost in ash and clinker withdrawn from boiler pits. The following results are given by Mr. W. G. Wilcox:[1]

	Per Cent.	Per Cent.
Overfeed stokers	**25 unburned carbon in the ash**	**= 4·6 actual coal lost.**
Chain grate stokers . . .	**35 ,, ,, ,,**	**= 6·1 ,,**
Hand-firing	**35 upwards ,, ,,**	**= 6·5 [2] and upwards.**

In powdered-coal firing less than one-half of 1 per cent. carbon will be found in ash and clinker when conditions are properly adjusted.

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[1] *American Chemical Society*, May 31, 1918.

[2] Slight difference evidently due to analysis of coals used.

CURVES OF COMBUSTION EFFICIENCIES, &c.

In Fig. 4 a series of curves applicable to the working of solid fuel furnaces are given. From these it will be seen at a glance how rapidly the overall thermal efficiency of furnaces heated by means of solid fuel decreases with the increase of excess air, which may be due to incorrect design or careless operation.

Take, for instance, the curve showing the relation between the percentage of CO_2 in the waste gases from a furnace and the corresponding preventable fuel loss.

In this case it is assumed that when the CO_2 content has dropped to 1·5 per cent. the amount of excess air is so great that all the heat liberated from the fuel is utilised in heating this excess air to a sufficient temperature to maintain an efficient chimney draught. The curve shows that with the usual CO_2 content of 5–6 per cent., as in hand-firing practice, the preventable loss is as high as 25 per cent. of the total fuel burned, and as the CO_2 content drops below this figure the preventable loss increases very rapidly. On the other hand, with a CO_2 content of 14–16 per cent., representing average practice for powdered-coal firing, the preventable loss becomes almost negligible.

From the temperature curve it will be seen that a waste gas temperature of 500° C. corresponds with an excess air value of 430 per cent., and it has been assumed that conditions under which there is an excess of air equal to 500 per cent. will be the limit at which preventable loss will occur, a sufficient chimney draught being assured at the same time.

It will be noticed that the CO_2 content may be dropped from the theoretical maximum of 20·7 per cent. to about 11 per cent. with a corresponding loss of efficiency of only about 5 per cent. After this, however, as the CO_2 content is lowered the loss of efficiency increases rapidly. A CO_2 content of 14–16 per cent. can be considered exceptionally good practice, seldom regularly obtained with solid fuel and hand-firing.

Consider next the curve showing the relation between CO_2 content of the waste gases and excess air supplied to the furnaces over and above the quantity theoretically necessary to burn the fuel.

Owing to its lump formation and to the usual methods of burning solid fuel the complete oxidation of the carbon cannot take place at a sufficiently high rate under ordinary conditions of firing unless some excess air is supplied. This excess, however, is usually much higher than is really necessary, and inspection of the curve connecting CO_2 with excess of air shows how rapidly the CO_2 content drops with increase in the supply of air.

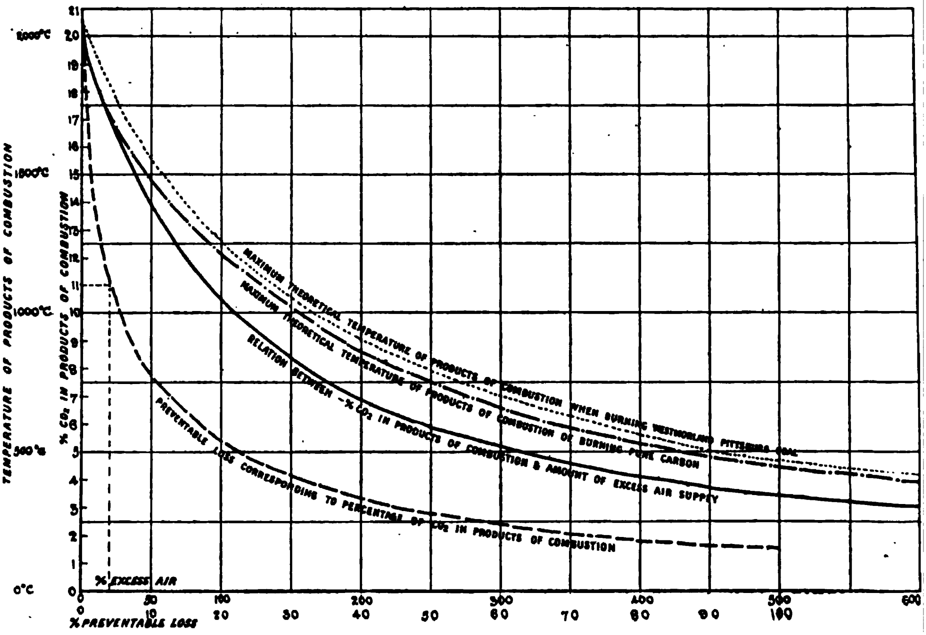

FIG. 4.—Curves showing maximum theoretical temperatures obtainable with varying quantities of excess air, when burning pure carbon and bituminous coal, also showing preventable losses due to excess of air supply.

The other two curves shown indicate the relation between the theoretical maximum temperature of the products of combustion when burning pure carbon and that when burning a representative sample of bituminous coal when supplied with no excess air, and also for varying proportions of excess air.

From these curves it will be seen that with even 25 per cent.

excess air the temperature of combustion falls 300° C., whilst with the general average of 300 per cent. excess air the temperature is less than one-third of the possible maximum when no excess air is present. Thus with coal in powdered form the oxidation of the small particles is instantaneous, preventable loss is very small, and very nearly maximum flame temperatures are obtainable.

The extreme importance of the effect of excess air on resultant combustion of fuels has not been sufficiently realised, and emphasis on this fact cannot be too strongly made.

GENERAL CONSIDERATIONS RELATING TO SUCCESSFUL APPLICATION OF PULVERISED FUEL.

In the application of powdered-coal firing, the five chief points to be constantly kept in mind are: (1) Elimination of the explosion danger; (2) efficient drying of the raw coal; (3) fine pulverisation; (4) avoidance of complicated equipment; (5) reliability of fuel supply.

(1) *Elimination of the Explosion Danger.*

It is evident from reports received by the author that several accidents occurred in the early development of systems depending upon the transportation of coal dust in suspension in a current of air.

Mr. S. H. Harrison[1] mentions the occurrence, several years ago, of a disastrous explosion at a large pulverised coal plant due to blowing the fuel through large ducts by means of fans. "This method of transportation should be condemned; a spark from a motor or from defective wiring may ignite this highly inflammable mixture." In present-day systems of this description the mixture of coal dust and air as supplied through the conveying pipes is not of an explosive nature, so long as the correct working conditions are maintained, and this is the only feasible manner of supplying powdered coal to numbers of very small furnaces, but the disadvantages of such systems appear to outweigh the advantages when fuel is to be burned in considerable quantity.

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[1] *Engineering Magazine*, February 1916.

It appears to the writer to be far preferable to distribute the powdered coal into bins at the boilers or furnaces, thereby preventing storage in bulk at any one point.

(2) *Coal Dryers.*

It is quite essential that all coals be thoroughly dried, and for this purpose efficient apparatus should be installed. The coal at the termination of this process should leave at a temperature not higher than 250° F., and with a moisture content under 1 per cent, otherwise overheating is likely to take place in the dry coal storage bin, or if used at once, overheating, and possibly firing, will be experienced in the pulverisers.

That coal dust should be as dry as possible is necessary for the satisfactory transportation of the fuel by any of the usual means: screw conveyors, air pressure, or in a current of air. This is a point worth special consideration in this country, where the atmosphere may contain considerable moisture, for pulverised coal will readily reabsorb water from the air and become sticky and difficult to handle.

When moist, coal dust will naturally coagulate and the advantages of initial fine pulverisation will be entirely lost, the fuel passing into the furnace in small lumps instead of in intimate mixture with the air supply.

It has been stated that dust-settling chambers in connection with coal dryers should be avoided, for there is a danger of the accumulated coal dust overheating and firing, which may well cause an explosion of the mixed gases and coal dust in the chamber, especially when cracks develop in the brick walls of the chambers, thus allowing the infiltration of air.

It is therefore considered preferable to exhaust the dust-laden gases from the dryer by means of a fan and to remove the fine dust in a cyclone separator.

The danger of explosion in dust-settling chambers is perhaps a very remote one, for the Cummer dryers are as a rule fitted with settling chambers, and the author has inspected Cummer dryers which have been running for years without any such mishap.

With further regard to this question of thoroughly drying coal for pulverisation, and in reference to the power required for the drying process, Mr. C. J. Gadd[1] makes the following statement: "If the moisture is allowed to exceed three-fourths of 1 per cent., operating troubles will result, and these become intensified the higher the percentage of moisture.

"It is easier to dry coal to one-half per cent. moisture or less than it is to maintain it in this state. This is explained by the fact that the moisture driven off from the coal in the process of drying saturates the hot air contained in the dryer cylinder. In this highly saturated condition the air follows the dried coal through the dust-proof conveying system to the enclosed storage bin. As the coal and air cool, moisture is precipitated and the volume of the air diminished, with the result that more warm saturated air is drawn from the dryer. These conditions, obviously, meet the requirements of a "still" of fair proportion.

"The precipitation of moisture resulting from the cooling process of the coal and air may be almost entirely overcome by placing ventilating shafts on the storage bin and the high points of the conveying system connected with the outside air. Each shaft should be equipped with a ventilator of approved type, and proper provision should be made to collect and deflect any condensation in the ventilating shafts, so as to prevent its return.

"It is thus evident that in the process of drying, through the medium of heat, a small quantity of the expelled moisture will find its way back into the coal after cooling. For this reason it is good practice to gauge the dryer so that the resultant product leaving the dryer will contain less than one-half of 1 per cent. moisture."

Table VI., prepared by Mr. Raymond,[2] is useful in showing the approximate consumption of coal for reducing the moisture content of coals.

The Fuller and Bonnot dryers are referred to later in the description of plant used with these systems. The Cummer dryer is another type which gives excellent results in practice.

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[1] *Journal of the Franklin Institute*, September 1916.

[2] *Proceedings of the Engineers' Society of Western Pennsylvania*, October 1913.

The following is a description of this drying process.

Three-quarters of the heated air and gases enter the cylinder by way of the 10⅛-inch diameter heat inlet openings, as indicated by the arrows. The balance enters the rear end. Through the hooded heat inlet openings at the front end of the cylinder the heated air and gases at highest temperatures come in direct contact with the wet, cold material as it enters. By the admission of cold air through the sliding doors in the dryer setting, the temperature of the heated air and gases is reduced towards the rear end to suit the material as it becomes drier and susceptible to injury from high temperatures. The lowest temperatures and the least circulation are found at the rear end of the cylinder, where the material is most dry and dusty. The idea is—high temperatures where the material is wet and cannot be injured, moderate temperatures where the material is partly dried, and low temperatures at the rear or discharge end of the dryer, where the material is practically dry.

TABLE VI.—*Fuel Required to Dry Coal.*

Percentage of Moisture in Coal.	Coal consumed per Hour in Pounds in Operating Dryer.[1]					
	160	230	350	540	715	900
	Capacity of Dryer in Tons per Hour.					
1	19·5	28·1	43·2	66·8	88·9	113·0
2	15·3	25·1	33·5	51·8	68·9	86·3
3	12·7	18·2	27·5	42·4	56·4	70·6
4	10·7	15·5	23·6	36·4	48·4	60·6
5	9·3	13·3	20·3	31·3	41·6	52·2
6	8·1	11·7	17·7	27·4	36·4	45·7
7	7·2	10·4	15·7	24·1	32·1	40·2
8	6·5	9·4	14·3	22·0	29·3	36·7
9	5·9	8·5	12·8	19·8	26·4	33·0
10	5·4	7·8	11·8	18·4	24·4	30·4
11	5·0	7·1	10·8	16·7	22·2	27·8
12	4·6	6·6	10·0	15·3	20·2	25·2
13	4·2	6·1	9·3	14·4	18·9	24·0
14	3·9	5·7	8·6	13·3	17·7	21·9
15	3·7	5·3	8·0	12·3	16·3	20·2

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[1] Coal to have 14,000 B.t.u. per lb.

The dryers seen by the author were fitted with mechanical stokers, but they can be hand-fired or arranged for use with powdered fuel. As a rule, when drying coal the dryer is provided with a dust-settling chamber and the exhaust fan is placed on the chimney side of this chamber and not directly on to the head of the cylinder.

The Ruggles-Coles dryer has been extensively used in America for drying coal. A " phantom " view of this apparatus is shown in Fig. 5.

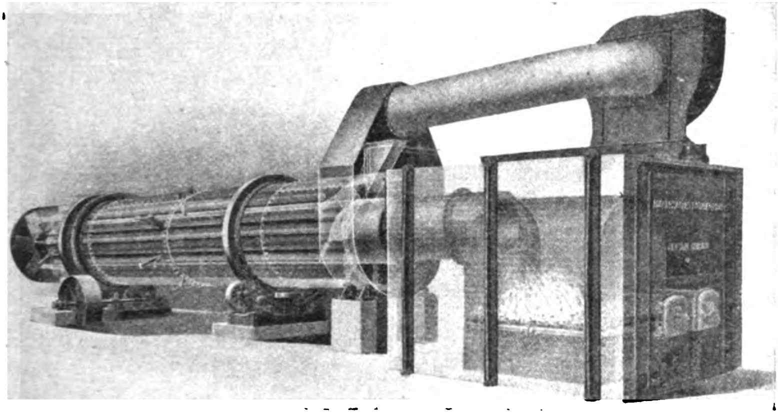

FIG. 5.—Ruggles-Coles Dryer.

In this case the hot gases from the combustion chamber enter the central tube of the dryer and pass through to the end housing without coming in contact with the fuel to be dried. The gases have then cooled down sufficiently for passing over the fuel on their way back through the cylinder to the exhausting head seen in the illustration.

(3) *Fine Grinding.*

For boiler firing and for use in metallurgical furnaces fine grinding is essential, otherwise instantaneous and complete combustion is impossible, the result being loss of unburned carbon in the ash and slag deposit in the combustion chamber or on the boiler tubes.

In one instance the pulverising plant was changed so as to obtain a product, 95 per cent. of which would pass through the 100-mesh screen; previously, coal dust ground to a fineness of 88 per cent. through the 100-mesh screen was used. After the change had been effected definite tests showed an increase in furnace efficiency of 12 per cent., and whereas with the coarser fuel ash troubles were constant, these were almost entirely removed when the finer coal dust was used.

(4) *Simplicity of Equipment.*

In this connection it will be interesting to make reference to the trend of opinion in Germany, where the use of fuels in pulverised form has undoubtedly been developed to a considerable extent during recent years upon lines of simplicity of machinery and handling plant. The following is a review of German practice:[1]

"In German plants particular attention is directed to simplicity of construction of the grinder, in which respect the German construction differs materially from American, and even though some typical American crushers—*e.g.* the Fuller–Lehigh—have been adopted in some German plants, as a rule they have not found ready application in that country, and for the same reason the high-speed machinery of this type built in Germany itself has not been much used.

"Where the plants using powdered coal have efficient repair shops and skilled mechanics available, oscillating crushers and similar apparatus can be used without much difficulty and with certain advantages; otherwise, however, the saving effected by their use will be more than eaten up by interruptions in the operation of the plant.

"In the modern German plant nearly everywhere one finds slow-running grinders with a large area of crushing, mainly of the ball and tube mill type. The larger amount of power consumption as compared with high-speed machinery does not particularly matter here. Ball and tube mills are as a rule located one over the other, so that the grist produced by the ball mill can go directly to the tube mill and be converted into fine powder.

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[1] *Journal of the American Society of Mechanical Engineers*, November 1915.

"In order to improve the screening action, several types of ball mills have been placed on the market; for example, the so-called Cementor mill of Polysius, Dessau, Germany. Contrary to the usual practice in ball mills, this construction has unperforated crushing plates, these plates being located between the walls in such a manner as to form stages with each other. With this construction, the grist is forced to run through the entire path of the grinding, passes over the sieve, and is then partly returned in a uniform manner into the grinding drum.

"The high cost of foundations which such an arrangement involves, and the effort to simplify still more the grinding, led to the design of a machine which could carry out the crushing and fine grinding in one continuous series of operations. This resulted in the design of a combined crusher and grinder, forming one cylinder, a design particularly adapted for use in steel mills because of its extraordinary simplicity. This type of machine, called "Solo" mill, is likewise built in Germany by G. Polysius, Dessau, and consists of a seamlessly welded sheet cylinder running in circular bearings. This cylinder is divided by a wall into two chambers, one the crushing chamber with hard steel plates and steel balls, and the other the fine grinding chamber with Silex lining and quartz stones. The crushing chamber is surrounded with screens, and is enclosed in a sheet steel jacket, and can crush pieces as large as a man's fist. This grist then falls through slots at the end of the crushing chamber upon screens over which it travels, just as in the Cementor, to the admission side of the grinding mill. What remains over the screen is carried back into the crushing chamber, while that which passes through the screen is delivered to the grinding chamber and handled there.

"As compared with the oscillating and Fuller mills, this design has the advantage of handling pieces to the size of a man's fist; as compared with mills which require special separators, as in the Raymond crusher, there is the advantage that the Solo mill uses no cyclones, &c. In addition to that, there is the very important consideration that this type of mill insures to a very large extent against the occurrence of fires and explosions; where the material handled has to be transferred from one apparatus to another, it is very difficult to provide against its escape and the formation of inflammable or explosive mixtures with air. In this case, this source of danger is eliminated to a large extent, and the author states that explosions have never occurred in mills of the Polysius type. The objection is often made to crushers operated with screens on account of their rapid wear; in the Solo mill these screens consist of perforated steel sheets of high resistance, in addition to which the construction is such that large pieces of iron that cause most of the wear cannot reach the screen."

In this account one or two points are of special interest. The preference maintained for the use of ball and tube mills as against high-speed mills of the Fuller or Raymond types has not been ratified by American engineers.

The large amount of power required for the ball and tube mill outfit combined with high cost of foundations are serious objections, and in practice it is understood that the cost of maintenance for the so-called high-speed mills (140 revs. or so per minute) has not been greatly in excess of the upkeep cost of ball and tube mills working in America. The Raymond mill certainly requires additional power for extracting the fine coal dust by air suction from the mill, but, as regards screen damage, most mills of this type, such as the Fuller, are fitted with heavy grid-protecting cylinders, which prevent pieces of iron, which have not been removed by the magnetic separator, from piercing the fine screen.

Accidents of this nature to the screens of Fuller mills have been reported, but these have been very infrequent when efficient magnetic separators have been installed, and the operation of changing a screen only means a delay of half an hour at most. Any damaged screen can be repaired and re-used, and the actual wear of mill screens is inconsiderable.

(5) *Reliability of Fuel Supply—Transportation and Storage of Coal Dust.*

It will be readily acknowledged that it is not very wise to rely entirely upon powdered coal stored in bulk at any one point if this can be avoided. If the fuel supply for a whole works or department is located at one point, any accidental breakdown of the fuel transport machinery will cut off the supply to the whole plant. Apart from this reason, there is always more danger of spontaneous combustion in a large mass of coal than in smaller quantities. Consequently it is best to convey the coal as it is pulverised to bins at the boilers or furnaces, which should have sufficient capacity to carry over any short period of breakdown of mill or transport gear. The use of screw conveyors has for these reasons many adherents in America, and is to be preferred in cases where they can be conveniently applied. Where greater risks can be taken, or for special purposes, one or other of the several means of conveying coal other than by screw conveyors can be used to greater advantage.

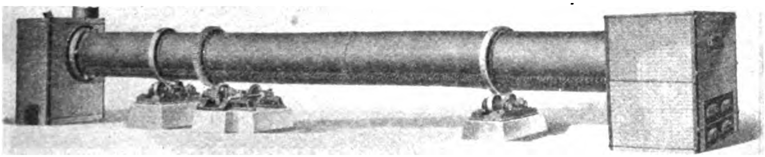


FIG 6.—The Bonnot Rotary Dryer.

SYSTEMS.

"HOLBECK" (BONNOT) SYSTEM.

The Bonnot dryer (Fig. 6) consists of but a single shell, and the hot gases from the furnace pass directly over the fuel to be dried. In America thirty or more installations are now in successful operation. At most of these plants the Bonnot pulverising mills and dryers are in use, but in some cases other standard types have been adopted. The arrangement may necessitate a tortuous line for the main supply pipe, but any increase in the number of curves or bends apparently only requires additional pressure on the air supply or the provision of booster mixing fans at certain points. The course followed by the coal after delivery at the track hopper and up to the pulverising mills is the same as in all other systems.

In the Bonnot pulverising mill (Fig. 7), the powdered coal is delivered into the cyclone separator, whence it passes into the storage bin, and is extracted therefrom in quantities controlled by the speed of the feed screw and mixed with air through the medium of a high velocity fan in the mill house. Approximately, 40 to 50 per cent. of the air required for combustion is mixed with the coal dust in this manner, the mixture travelling through the supply pipes to the furnaces, under a pressure of some 10 ounces per square inch, and at a rate of 5000 feet per minute (roughly one mile per minute).

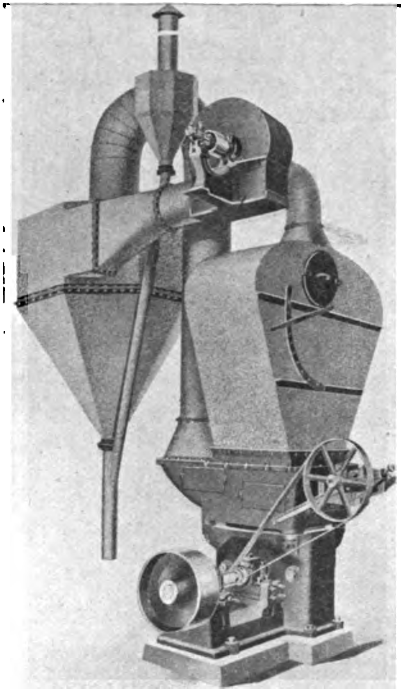


FIG. 7.—Bonnot Pulveriser and Air Separator.

Any portion of this air and coal dust mixture not used in the furnaces is returned by the loop system to the cyclone separator wherein the coal dust is collected and the air with which it was mixed is discharged into the atmosphere. The extracted coal dust is returned to the storage bin for remixing in the mill-house fan. There must necessarily be times when only a few furnaces are in operation, yet the full supply of coal dust must be maintained as for maximum requirements. Power wastage at the mill-house mixing fans and for Booster fans must be considerable under such circumstances.

In order to ensure that the proportion of coal dust and air in the supply pipe is constant, a special automatic regulator is used. The action of this regulator is dependent upon the rate of air supply to the fan. As the demand increases, so does the air-control cylinder valve open, and by means of a self-adjusting control device the speed of the coal dust feed screw is increased or reduced, and a greater or less quantity of coal dust is fed into the mixing fan.

In the author's opinion further improvements have yet to be made in connection with this automatic control apparatus. The idea is very well conceived, but the actual apparatus is somewhat too complicated or too delicate to stand the test of rough mill-house use.

Burners.—The mixed air and coal dust is taken to the burners from the supply main by means of ordinary branch pipes in a similar manner to the supply of gas.

Branch control shutters or valves are placed close up against the supply main, in order to prevent the settlement of coal dust in the down pipes. The secondary air for combustion is delivered through a main air trunk to the burners in the usual manner.

As a rule, the Holbeck burners are fitted with end cover plates, and very often some of the ash slag deposited at the burner outlet is removed by raking it through the back ends of the burners. For high-temperature work the burners are water-cooled, which would appear to be a disadvantage, as it involves the addition of a complicated network of water pipes and a wastage of water.

Why water-cooling should be adopted with this system is not readily explainable, unless it is that on account of the more perfect mixing of the coal dust with the air supply before the fuel enters the furnace, combustion takes place closer to the burner orifice than with other systems. Coal dust and air are, however, often mixed some feet away from the orifice of the burner pipe in cases where water-cooling is not employed, and it would seem that the mixing of the coal dust and air would be almost the same in these instances as for the Holbeck system.

"QUIGLEY" SYSTEM.

Description of Mill-House Plant.

An outlay arrangement for a Quigley mill-house plant is shown in the "Report," so that it will only be of interest to reproduce a general view.

Fig. 8 represents such an installation in elevation, and the course of the coal from track hopper to blowing tank can be readily traced. The coal on delivery is put through the preliminary crusher; it is elevated to the magnetic separator, over which it passes to the crushed-coal bin. From this bin the coal is fed to the Ruggles-Coles dryer, which is fitted with an exhaust fan for removing the products of combustion, water vapour, and fine dust, the latter being deposited in the cyclone separator seen above the dryer. At the dryer discharge end the coal is elevated to the dry-coal bin, from which it is fed by gravity into the Raymond pulveriser.

The freed air in the cyclone separator is returned to the pulveriser. The positions of the motors for driving the plant, and that of the air compressor for coal-dust transportation to the furnaces, are indicated.

Air-Pressure Transportation of Coal Dust.

Fig. 9 shows the powdered-coal storage bin, the blowing tank, and the transport pipe line, in which semi-automatic switch valves are provided for diverting the coal dust into the supply bins at the furnaces.

The quantity of coal dust sent to any particular furnace bin is read off on the scale of the weighing platform on which the blowing tank is situated.

The cycle of operations is detailed on p. 19 of the "Report."

It will be noticed that every furnace bin is fitted with a cyclone coal dust delivery separator. The air used in the propulsion of the fuel from the blowing tank at the mill house escapes through the vent pipe attached to the cyclone separator.

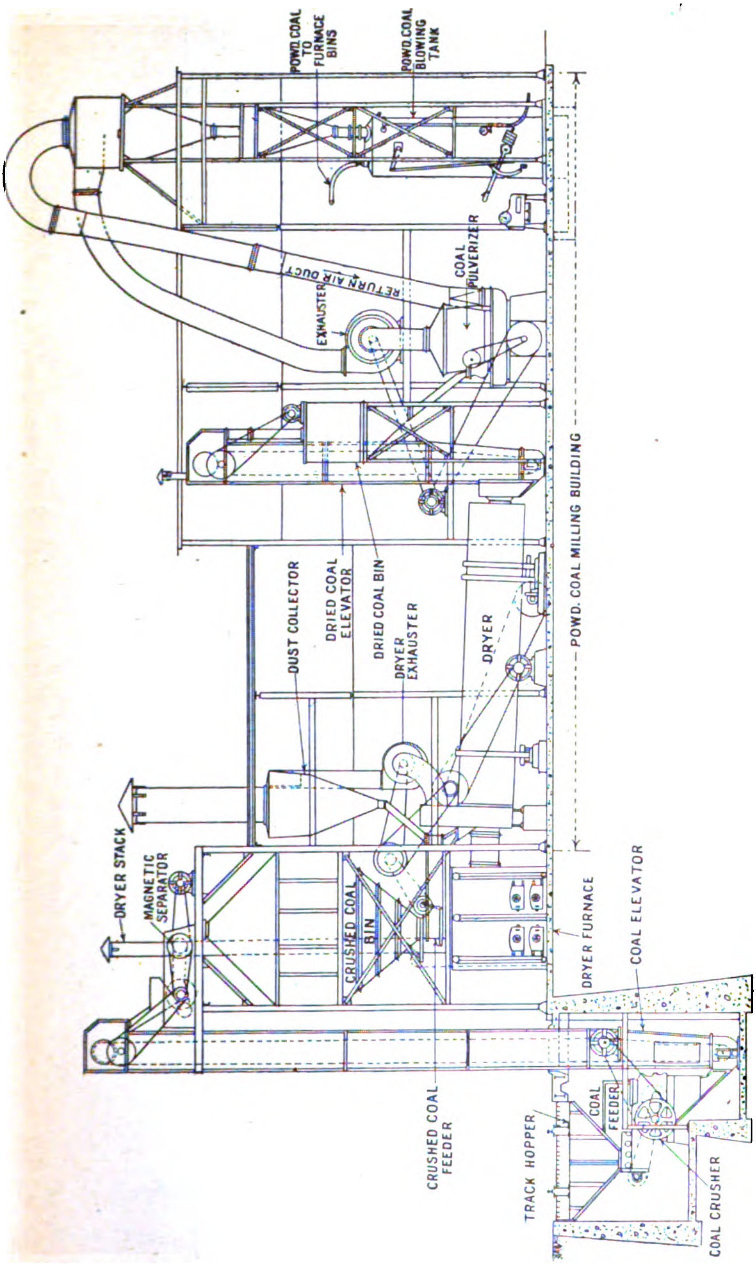


Fig. 8.—Powdered Coal Installation showing "Raymond" Air Separator Mill and "Quigley" Blowing Tanks.

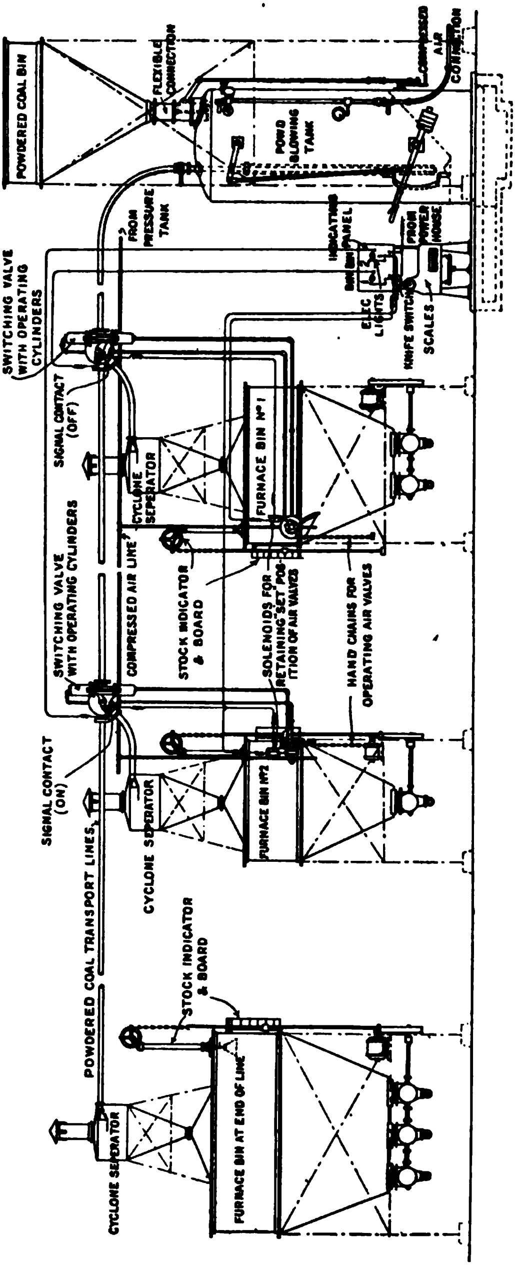
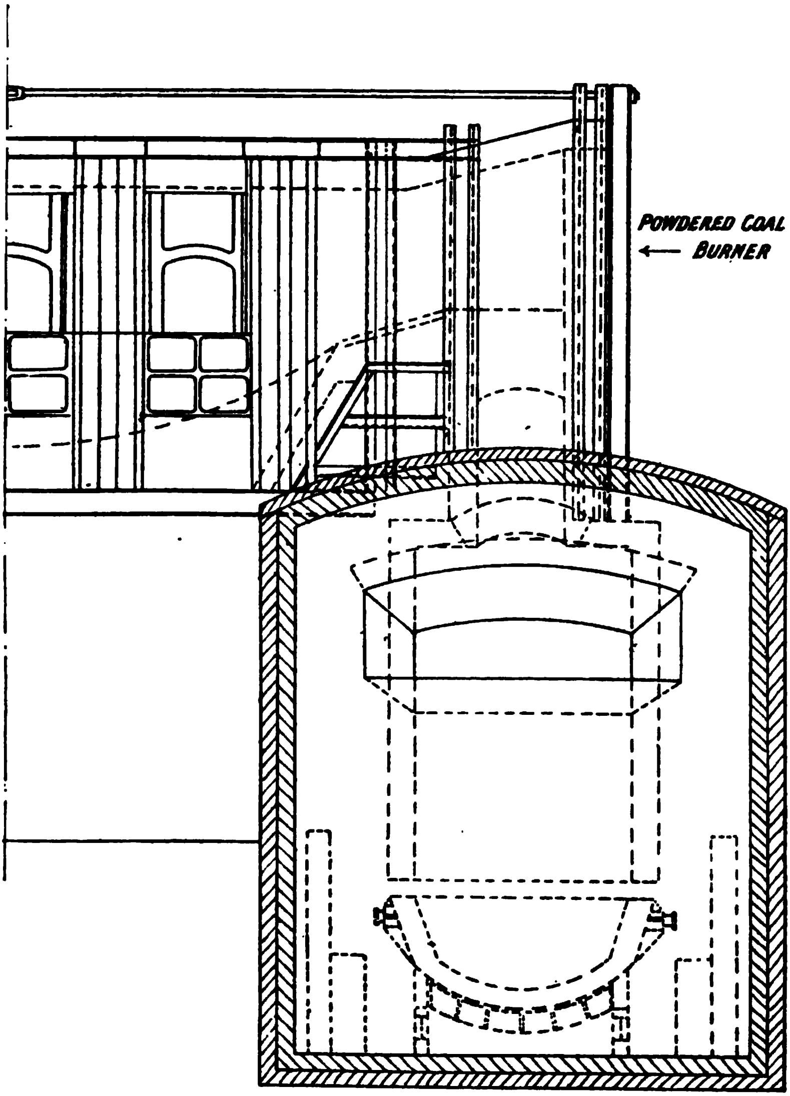


FIG. 9.—"Quigley" Semi-Automatic Bin Filling System.



owing ash bogies beneath downtakes.

itch Patents.)

To face p. 80.

That this system has distinct advantages in connection with the delivery of coal dust through ordinary supply pipes, as for gas or water, is unquestionable. Coal dust can be readily conveyed into the bunker cylinders of a ship in dock, or special colliers can be used for coaling ships in harbour or at sea.

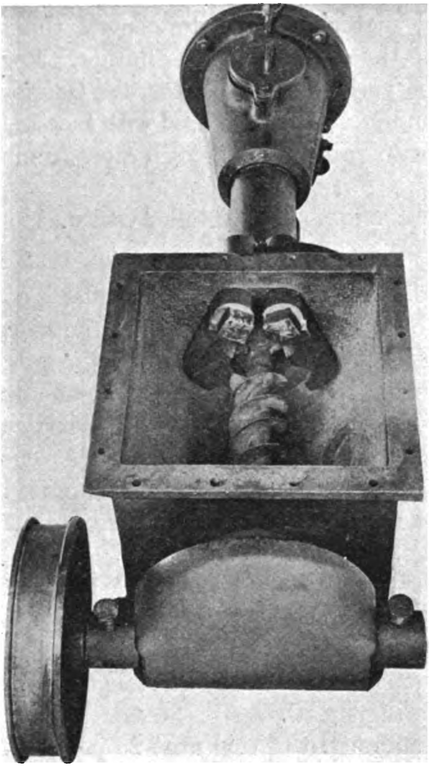


Fig. 10.—Constant Speed Feeder.

It has been suggested that a coaling barge, having air-tight bunkers for powdered coal, would be most suitable, and each bunker would be provided with one of the semi-automatic switch cylinders mentioned above.

Coal-Dust Feeders.

The universal practice is to make use of the single or double flight screw feeder. In most systems the worm is operated by a variable speed motor in order to control the quantity of coal dust fed into the air-blast at the burner. For the purpose of eliminating the variable speed motor, the Quigley constant-speed feeder shown in Fig. 10 has been used with success, and it is possible in this manner to run a number of feeders from line shafting.

THE "FULLER" SYSTEM.

This is undoubtedly the pioneer system for the use of powdered coal. The chief feature of a Fuller installation is simplicity of lay-out from the raw coal track hopper to the furnaces. The coal and coal dust in the mill house are handled by means of bucket elevators and screw conveyors, and the latter means of transportation is generally employed to carry the coal dust to the points at which fuel supply is required. The standard mills are of the screen separator type, the pulverised coal being delivered into the boot of a bucket elevator discharging into the screw conveyor transport line.

Fuller mills can equally well be made with air-separator fans, but as a rule the makers prefer to supply their screen mills rather than fit the mills with coal dust exhaust fans for the following reasons; these can be taken as applying to air separator mills in general.

(*a*) For equal output of coal dust 25 per cent. to 50 per cent. additional power is necessary for air-separator mills.

(*b*) Suction fans for air separation must be run at high velocity, 1000–1250 revolutions per minute, depending on fineness required, quantity of coal per hour, position of fans in relation to cyclone separators, &c. At this speed fans having wheels of 42 inches diameter or so bear a tremendous strain. The wearing effect of coal dust on the fan blades is often excessive, and renewals of fan blades will be required every few months.

(*c*) The power required for this operation to remove 4 tons of coal dust per hour is some 35 horse-power, whereas a bucket elevator used in conjunction with a screen separator mill requires but 5 horse-power for the same duty.

(*d*) In a measure, Fuller screen mills are provided with suction slow-speed fans integral with the grinding elements. The action of these fan blades is sufficient to collect the dust from the grinding zone and to force it through the screens. The power to operate these fan blades is but 1 per cent. of the power taken by the mill, whereas for air separation the power for the exhausting fan may be 35 or 40 per cent. of the mill power.

It is claimed that the Fuller mill has a larger grinding surface than any other mill of its kind, due to the circular movement of the pushers and balls which operate in a concave-shaped grinding ring. The effective pulverising surface is, therefore, greater than in mills fitted with vertical shafts to which rollers are attached, in which case effective grinding only takes place at the circumferential points of contact between the rollers and the bull ring.

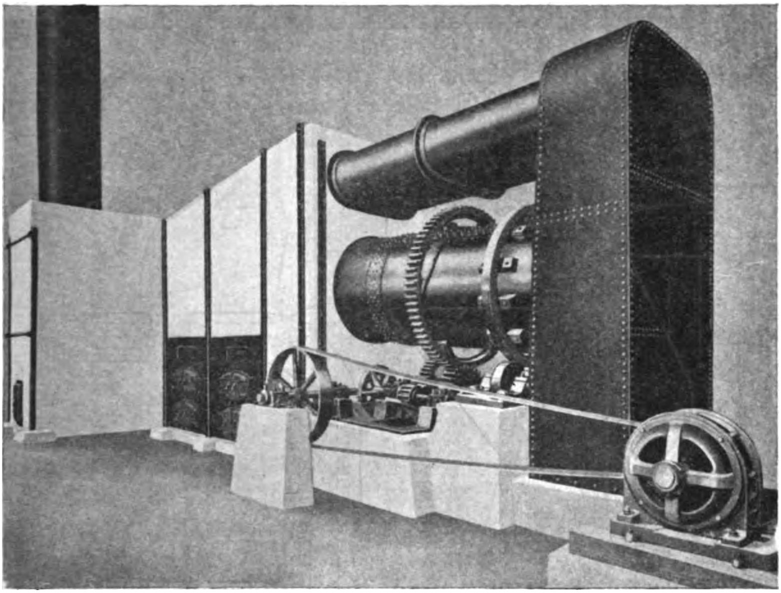


FIG. 11.—Fuller Rotary Coal Dryer.

The Fuller dryers differ from the Bonnot, Ruggles-Coles, and Cummer dryers in that the heating chamber surrounds a considerable portion of the drying cylinder. In this way the heating gases come in contact with the walls of the cylinder; they then pass through a duct to the end of the dryer, returning through the cylinder in direct contact with the coal. This type of dryer is shown in Fig. 11.

The "Fuller" equipment for locomotives is referred to in the "Report" and on p. 109 of this paper.

The "Bergman" System.

Mr. L. H. Bergman advocates the bin system of fuel storage at the furnaces or boilers, and he uses standard mill-house equipment such as Ruggles-Coles dryers, Raymond Mills, but for certain special cases an air and coal dust mixture system is supplied.

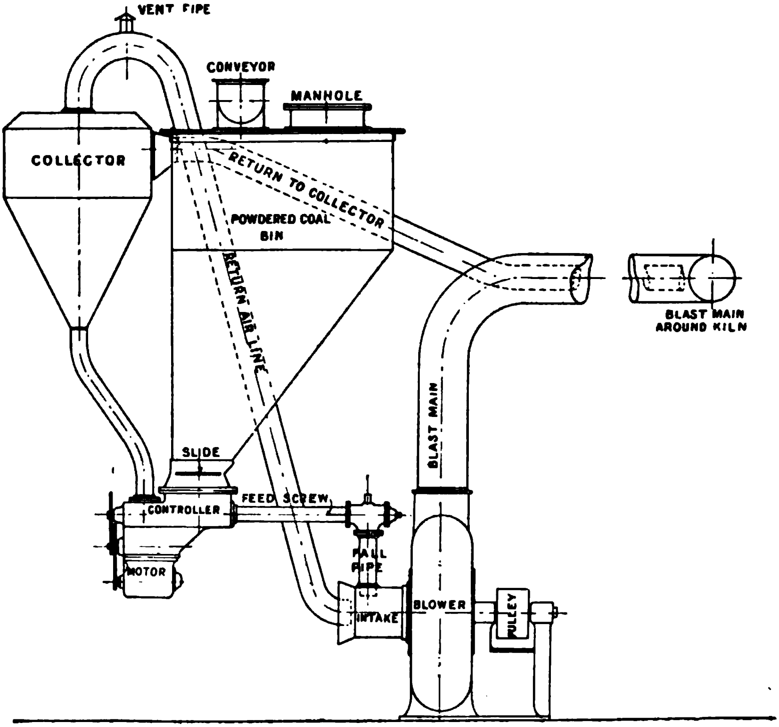


Fig. 12.—Powdered Coal System for Brick Kilns.

A diagram of this system is shown in Fig. 12. It differs from the "Holbeck" in that the surplus mixture not used in furnaces is returned to a cyclone separator, but the coal dust extracted therein, instead of being returned to the main fuel bin, is returned to the coal feed-screw, the freed air and fine dust which may be still in suspension is withdrawn direct to the mixing fan inlet instead of being exhausted into the atmosphere.

This equipment forms a self-contained plant suitable for a small furnace shop. Such an arrangement can often be used to advantage in conjunction with the usual bin system for other parts of the works, and forms a supplementary system for use under special circumstances. The powdered coal is delivered to the fuel bunker by screw conveyor and the mixing operation effected through the medium of the rotary fan.

The author is indebted to Mr. Bergman for many of the comparative results between powdered-coal fired furnaces and those heated by other means which are mentioned in this paper and the "Report."

"COVERT" SYSTEM.

Mr. Covert has aimed at supplying specially designed apparatus to suit each individual application, and to this end the continuous coal dust and air mixture system shown in Fig. 13 has been devised.

This is again unlike the pioneer "Holbeck" system in that the return of surplus mixture is taken direct to the mixing fan inlet, there being, therefore, little waste power in dealing with this surplus fuel and air. Any deficiency is drawn from the mixing chamber at the top of the main fuel tank. Coal dust is injected into this mixing chamber by means of a small quantity of compressed air, and the actual supply of coal dust and air withdrawn is regulated by the diaphragm control shown at the top of the make-up pipe.

The special screw feeder supplied in connection with the "Covert" system is shown in Fig. 14. This arrangement of interconnected cross-feed screws ensures a regular feed and to a great extent prevents flushing.

Coal dust is conveyed by screw conveyor or by means of compressed air, and at one plant visited coal dust was transported by the latter method a distance of 1500 feet through 1782 feet of 3-inch pipe (allowing for bends and detours).

One or two of the more important points claimed for this continuous air and coal dust distributing system are:

(*a*) That the coal dust is not separated out after having once been mixed with air, and is, therefore, not subjected to an oxidising process more than once. This practically removes the difficulty experienced with other air and coal dust mixture systems as applied to low-temperature furnaces in which it is sometimes impossible to burn partially oxidised coal dust.

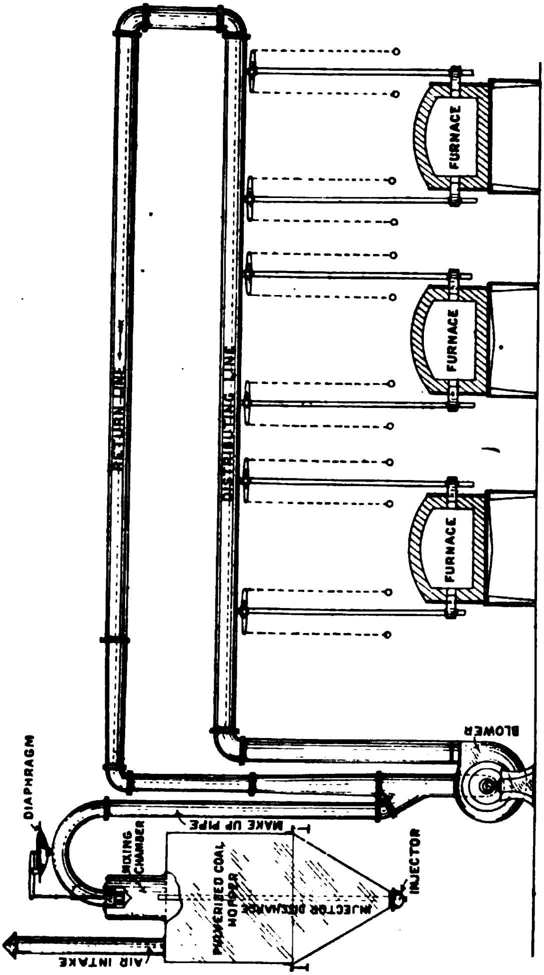


FIG. 13.—"Covert" System.

(*b*) In other systems the larger particles of coal dust, due to their momentum and inertia, pass the branch openings to furnaces and are returned to the main fuel bin; in consequence a collection or strata of coarse coal is often present in bins connected with such systems. In the Covert system all coal once taken from the bin is in constant circulation until burned, any coarse particles being ultimately split up in the mixing fan.

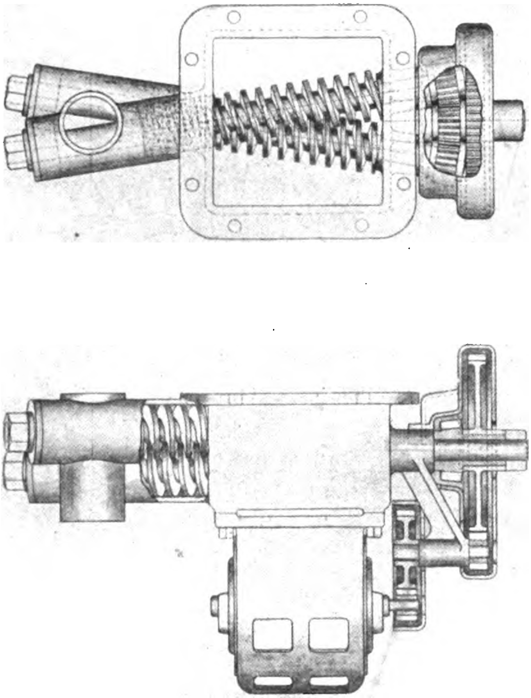


FIG. 14.—"Covert" Screw Feeders.

(*c*) The mixture is supplied at constant velocity, and is, therefore, at constant richness, no matter how many furnaces may be working at one time.

THE "AERO" SYSTEM.

The Aero mill is a small compact pulveriser unit, and it has been extensively adopted in cases where a comprehensive mill plant cannot be entertained. As a means of pulverising fuel to a certain degree of fineness it has proved very satisfactory, but it will not produce coal dust at the degree of fineness required for efficiently heating certain types of metallurgical furnaces.

The pulveriser is shown open in Fig. 15. It is of the beater type, and no dryer is used as a rule. Coal is fed into the reciprocal feed chamber, coal and air entering together; the pulverisation and air-mixing takes place during the one operation. Rotary fan blades attached to the main shaft at the discharge end induce a current of air through the mill and remove the particles of coal.

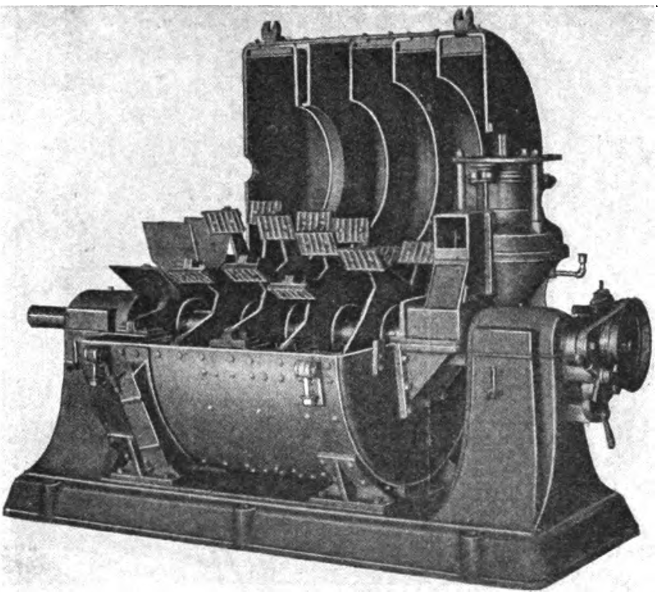


FIG. 15.—" Aero " Pulveriser Mill.

It can only be said that this is more or less of a crude type of apparatus in comparison with the comprehensive plants described, but it fills a gap where small quantities of pulverised coal are required.

Apart from particular applications where this unit is preferable, it can be made use of to advantage when preliminary experiments are to be carried out in advance of making a decision as to whether a complete mill-house plant should be installed.

"STROUD" SYSTEM.

Another type of small self-contained pulveriser apparatus is shown in Fig. 16. This apparatus belongs to the disintegrator

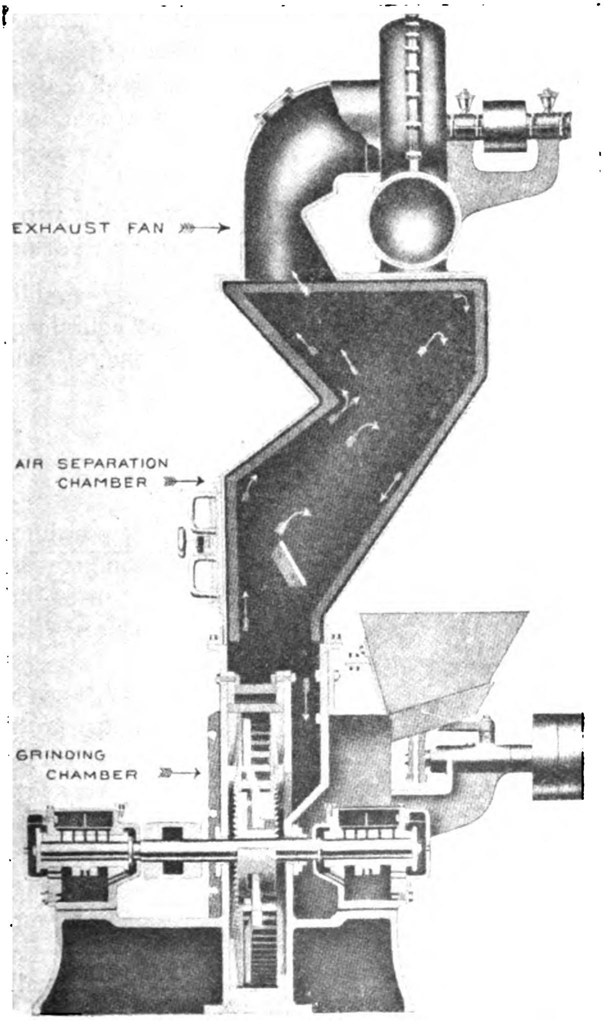


FIG. 16.—"Stroud" Air Separation Pulveriser. (View from front end.)

class of machines. Coal of ½ to 2 inch cubes can be fed into the pulveriser, and the lumps are thrown against each other and against the rough-toothed lining plates by the rapidly revolving beaters. When pulverisation has taken place the dust is extracted by means of an exhausting fan, fineness depending upon the speed of the latter and the velocity of the air current through the grinding chamber. Coarse particles fall back into the grinding chamber. Like the "Aero" this machine would be useful for supplying small quantities of pulverised coal and for making trials on furnaces prior to installing a complete mill-house plant.

The Locomotive Pulverised Fuel Company's and The Powdered Coal Engineering Company's Systems.

The special feeder mixers and carburetters supplied by these companies, together with the locomotive equipment supplied by the former company, are described in the "Report."

Applications.

Malleable Iron Furnaces.

Figs. 17 and 18 show the method of applying powdered coal to a malleable iron melting furnace in which temperatures between 3000° F. (1650° C.) and 3220° F. (1770° C.) can be obtained with air at 60° F. (16° C.), and higher temperatures will result with preheated air.

Melting conditions are under perfect control, and at this degree of heat there is of necessity little free oxygen present, so that the burning out of valuable elements such as carbon and silicon is avoided, and melting takes place with a very low loss.

By the use of powdered coal the flame can be directed on to the bath of metal; thus it becomes possible to dispense with the "top air" jets usually provided on hand-fired furnaces in order to force the hot gases away from the roof brickwork and on to the metal bath.

Mr. Joseph Harrington[1] has given a concise explanation of the radiant heat effect of minute incandescent carbon particles, the benefit of which is fully realised with pulverised fuel. For

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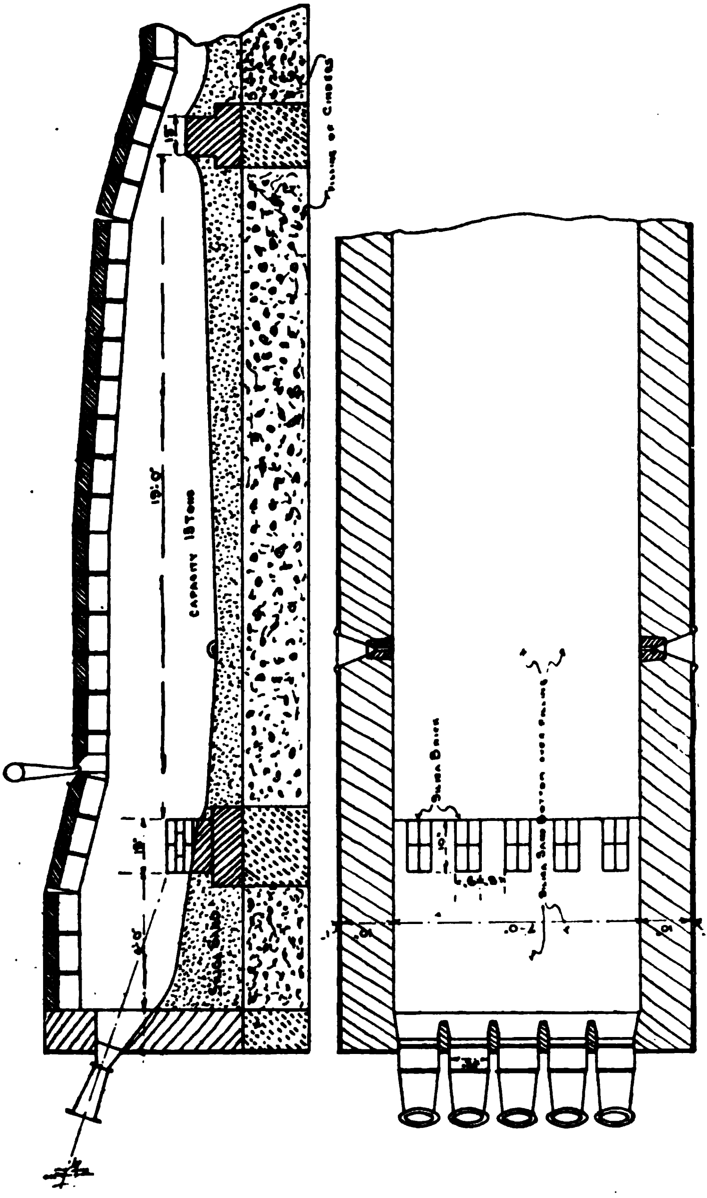
[1] *The Foundry*, October 1916 and December 1918.



Figs. 17 and 18.—Application of Powdered Coal to Malleable Iron Melting Furnace.

the information of those who may not be able to obtain access to this information, it will not be out of place to quote from Mr. Harrington's second article. When comparing older methods with that of coal-dust firing he remarks that in ordinary practice air, usually known as top air, is introduced into the furnace from above. This supplies the necessary oxygen for the complete burning of the hydrocarbon gases evolved in the fire-box; and also serves to force the hot burning gases down on to the metal bath.

It has been customary to apply this secondary air by means of from four to six nozzles, spaced across the top of the furnace and slanting downward towards the metal bath. It is almost obvious, however, that 2-inch jets of air spaced 15 or 20 inches apart will not have a character other than that of jets. The space between the jets is filled with furnace gas inadequately supplied with air, and in all probability it is this gas which finds its way along the furnace roof and eventually burns, if at all, in the rear of the furnace or in the flue leading to the stack.

Powdered Coal as a Gas.

Considering now the radical difference between this method and the conditions which obtain with pulverised coal in suspension in a stream or jet of carrying air, one must conceive of the powdered coal having the character of gas in order fully to appreciate the controllability of the flame both as to direction and velocity and extent. The nozzles in this case are placed in such a manner that the fuel jet itself is directed downward toward the hearth. The velocity of the jet being controllable, the flame can be made practically any length desired. By using a high-velocity jet it would be possible to cause the flame itself to directly strike the liquid iron and spread out in a continuous sheet over the surface of the metal, or to mingle intimately with the pile of iron on the hearth. On the other hand, it is equally possible to decrease the velocity of the jet to a point where it reaches the right part of the furnace close to the metal, and thereupon loses the velocity acquired at the nozzles, and becomes a floating mass of gas moving with relative slowness through the furnace. To hold the sheet of slowly moving but very intensely heated gas near the surface of the metal, a relatively thin, continuous sheet of air can be introduced in the same place that the top air nozzles ordinarily are located. It is obvious that this secondary air, if introduced in a uniform sheet the entire width of the furnace, at least, at the moment of its introduction, will spread out into a very thin layer, having a maximum of exposed surface and a minimum of gaps through which unburned gases can pass.

In the malleable melting furnace, after the pile has begun to subside, there is little or no tendency for the gases to mix, and the effect of the air curtain described, therefore, is to cause a stratification of the gases in the furnace. The hottest gases are held down in the furnace in direct contact with the metal bath. At the same time there is a certain protection to the roof of the furnace caused by the layer or stratum of air in immediate contact therewith. It undoubtedly will be conceded by melters that it would be desirable if the roof of a melting furnace could be lowered after the metal pile subsides and during the latter part of the heat until the clearance between the roof and the hearth should be cut in two. But it is necessary to have the roof a certain height in order to make it possible to charge the furnace, and this height, of course, has to be maintained at all times. However, the effect of lowering the furnace roof can largely be accomplished as previously indicated, and with a highly preheated air under control the incandescent, pulverised coal flame can be made to skim along the surface of the bath in direct physical contact therewith, and in the very best position to give up the maximum amount of heat thereto.

It is perhaps obvious from the foregoing that the beneficial result obtainable from the better contact of gas and metal and the utilisation of the radiant heat, is a quicker melt with less burning out of the desirable elements of silicon, manganese, and carbon.

With pulverised coal it is possible to get an incandescent front within a few minutes of the time of starting, even though the furnace be perfectly cold at first. The high temperature is maintained consistently until tapping is begun. It is inevitable that the iron should melt quicker under these conditions, and just as inevitable that the losses of valuable ingredients should be reduced. Slag troubles do not occur because the ash liquefies and runs down on to the metal bath, from which it is skimmed periodically with the rest of the slag. The conservation of the carbon, &c., has a directly favourable influence on the amount of high-grade iron to be charged, and a definite saving, variously estimated from 2 to 5 per cent., is the result.

Open-Hearth Melting Furnaces.

Burners.—For the general run of metallurgical furnaces burners of simple design are used. These consist mainly of an air-blast pipe into which the coal dust is fed from the screw feeder. The dust falls into the air stream, and in this way is carried into the combustion chamber.

Certain special burners or mixers have been designed, whereby a premixing of the coal dust and air is effected in one or more stages before the final mixture emerges from the burner nozzle.

With the simple type of burner having the one air-supply pipe, fine adjustment of the mixture can be effected by means of a natural-draught sliding cone section.

For melting steel in the open-hearth furnace it is desirable to project the flame on to the centre of the bath, so that at each reversal the one or other end receives the greater intensity of heat. Burners for this purpose are, therefore, generally operated with high and low pressure air, the burners being made with swivel joints, so that the flame can be projected in the direction required.

The usual type of burner is shown in Fig. 19, and screw-adjusting gear is usually fitted, so that the nozzle section can be moved in order to control the direction of the flame. This burner is for working with low-pressure air at the main supply, and with a small proportion of compressed air to effect thorough mixing of the air and coal dust through expansion of the high-pressure supply.

The second illustration, Fig. 20, shows a burner to work with compressed air only; the coal dust in this case is syphoned out of the fuel chamber.

It is general practice to arrange the burner nozzle in front of a natural-draught inlet port. Overheating of the burners does not take place, because at each reversal the burner is usually withdrawn and an iron slide lowered over the inlet port.

In certain instances this operation is automatically performed the starting and stopping of the air and coal dust supplies being operated by electrical control gear working in synchronism with the reversal of the chequer valves.

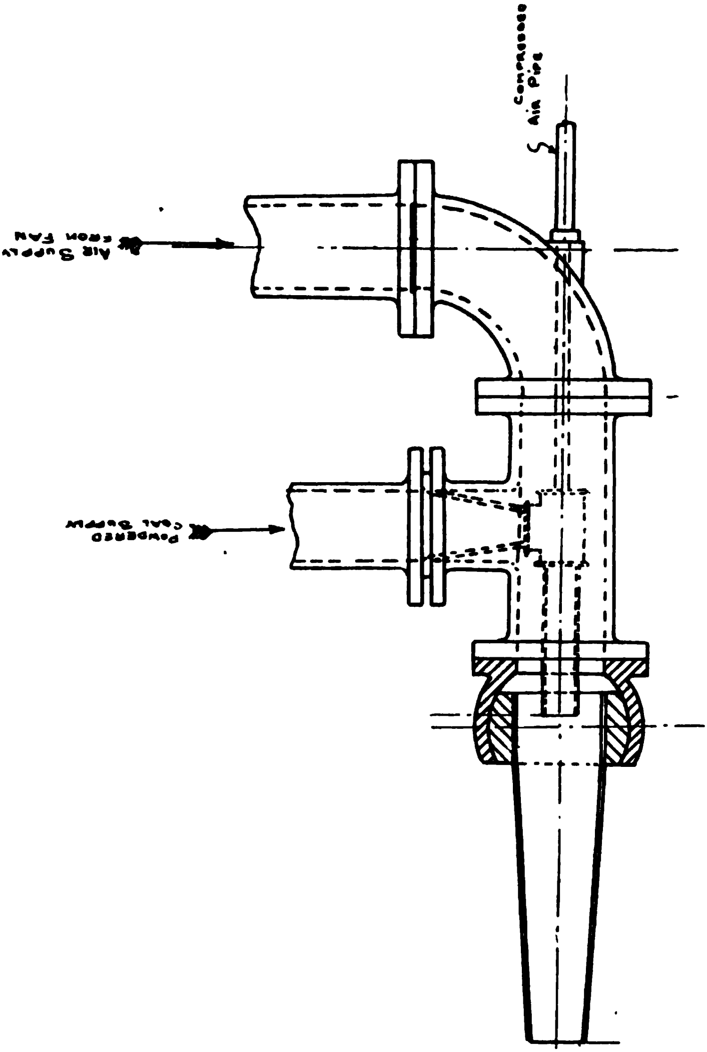


Fig. 19.—Usual Type of Powdered Coal Burner for Open-hearth Steel Melting.

The use of high-pressure air for open-hearth steel furnaces enables the full flame temperature to be developed in close proximity to the metal and avoids the overheating of the refractory walls.

The application of powdered coal to open-hearth furnaces has not been so generally carried out as for other purposes in steelworks, but of recent years much progress has been made.

It is quite possible to melt steel with powdered coal and cold air, but the time required under these conditions for melting is too long.

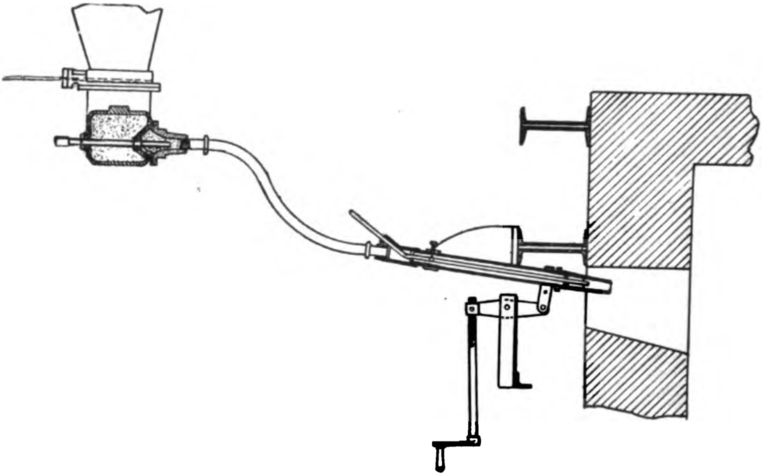


FIG. 20.—High-Pressure "Syphon" Type of Burner.

Preheated air is always used, and this is generally effected in the existing regenerative air chambers, in which much trouble was at first experienced with ash deposit. Furnaces heated by this means can be so designed as to overcome the ash trouble, and this can very often be accomplished on existing furnaces.

Fig. 21, Plate II., shows a 40-ton open-hearth furnace with ash bogies placed below the down-take flues, in which a very large quantity of the ash particles carried through the melting chamber is collected before the gases enter the checker-work.

With a suitable fuel, finely pulverised and applied in approved manner in conjunction with heated secondary air, excellent results have been obtained in America, and the use of powdered coal for this purpose has now reached a practical and successful stage.

This matter was recently referred to in *Blast-Furnace and Steel Plant* as follows:

"While for heating furnace work many kinds of coal are available for powdering, the list of available coals for open-hearth work is small. Small sulphur content and small ash content together with high volatile content are extremely desirable. Many failures of powdered coal for open-hearth work are due to the purchasing of a cheap coal. Regenerators must be so designed that fused ash can be deposited in a removable slag pocket before the flue gases reach the checker work. The latter must be fairly open. Good success has been attained by making the gas passages tubular without dead spaces or projecting corners which may favour deposit. From snowstorms it is known that snow drifts into places where the air is stagnant, and accumulates there. Ash in flue gases does the same. Easy bends of tubular construction and without sudden changes in cross-section are therefore recommended.

"To avoid deposits of ash, the coal must be very finely ground. The finer the coal, the slower the air current in which it will remain afloat. Installations of grinders much larger than absolutely necessary are recommended, because overloading of pulverising apparatus causes coarse grinding. If the grinding is fine enough, if the regenerators are properly designed, and if a good coal is burned, practically all of the ash[1] is carried out through the stack in the shape of a scarcely visible whitish haze. If these precautions are not used, and particularly if a cheaper grade of coal is used, frequent repairs to the furnace regenerator are necessary; in some places the regenerators have to be cleaned out every four weeks. There is consequently no saving in using a cheap coal, particularly in times of great demand for steel. The gain due to the avoidance of frequent shut-downs pays several times over for the difference in the price of coal."

Fig. 22 shows the application of powdered coal to a steel tilting furnace. It will be noticed that it is a furnace of the non-reversing type, the flow of the gases being always in one direction, which simplifies the installation, and incidentally it may be pointed out that the use of powdered coal enables the gas re-

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[1] Presumably that portion of the ash passing out of the melting chamber and over the slag pocket previously referred to.

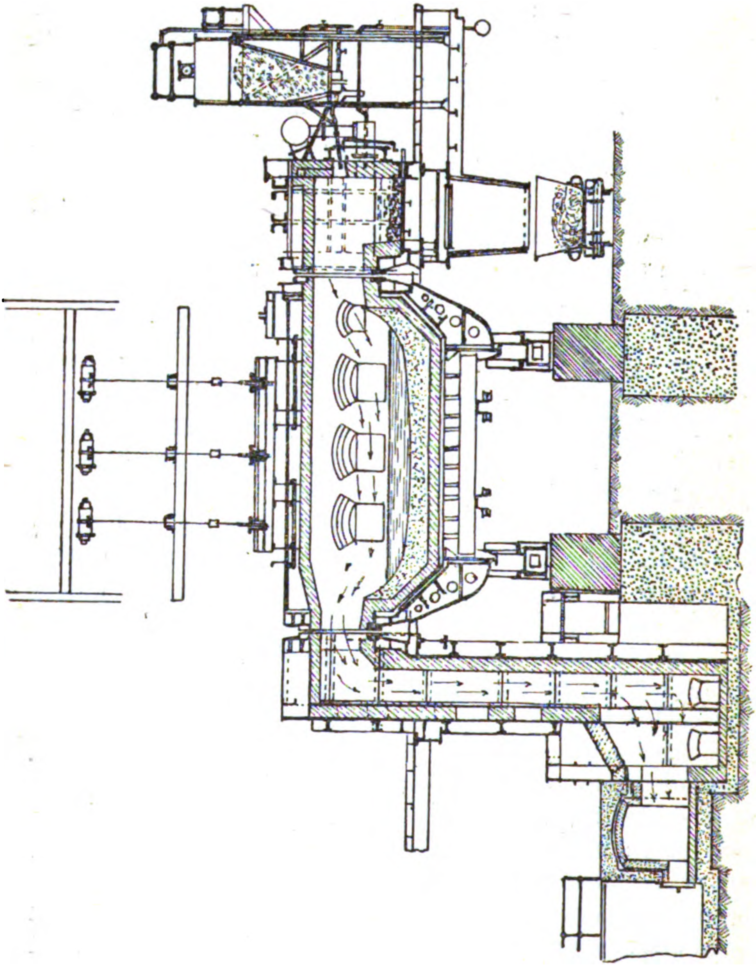

FIG. 22.—Powdered Coal Fired Tilting Furnace.

generators to be dispensed with. The figure has been taken from Mr. C. J. Gadd's paper previously referred to.

With regard to sulphur contamination of steel, this is no greater than with producer-gas. The sulphur contained in the coal is split up into such fine particles that it is immediately burned and the products pass off in the waste gases. In one case a coal containing 1·25 per cent. sulphur was used, and the analysis showed only 0·035 to 0·04 per cent. in the steel produced.

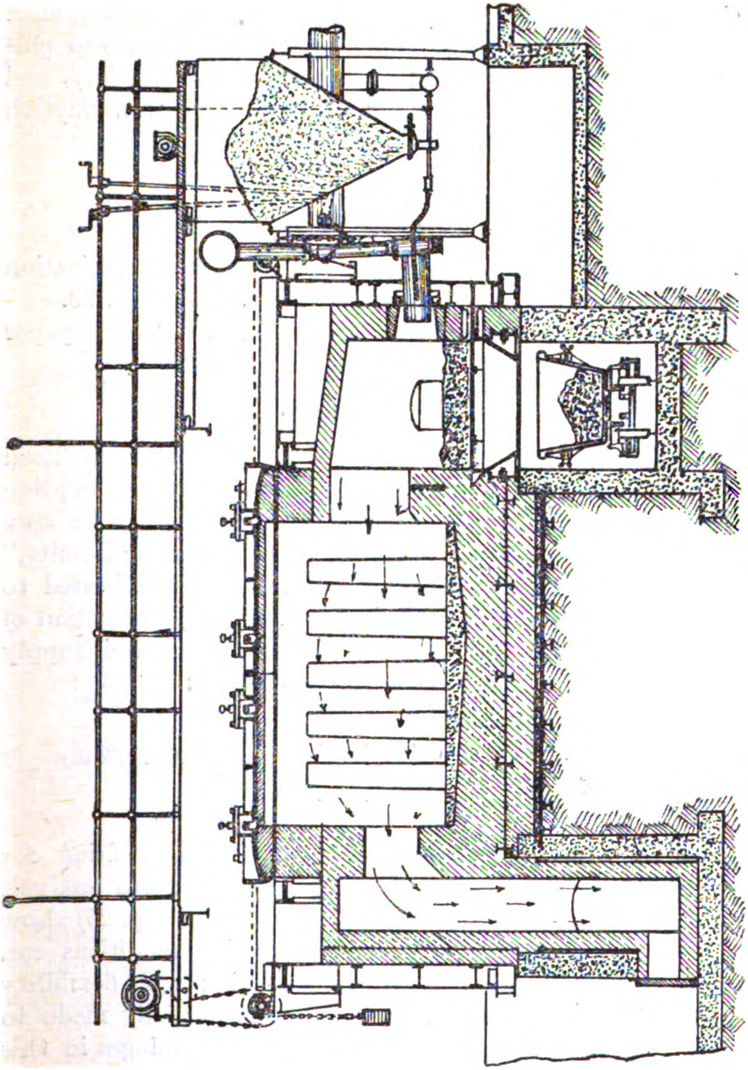

FIG. 23.—Powdered Coal Fired Soaking Pit.

Several figures relating to fuel consumption when using powdered coal are given in the "Report," the average being between 500 and 600 lbs. per gross ton of ingots cast. Reference may be made to certain results obtained in one instance, after conversion of a producer-gas fired open-hearth furnace to pulverised-coal firing: record monthly tonnages were obtained, and for 3218 tons melted in one month the overall fuel consumption was 441 lbs. per gross ton of steel.

Soaking Pits.

A powdered-coal fired soaking-pit, fitted with a combination high and low pressure syphon burner, is shown in Fig. 23.

This illustration has been taken from Mr. C. J. Gadd's paper previously referred to.

Puddling Furnaces.

Fig. 24 shows a very common type of puddling furnace fitted with waste-heat boiler and air-heating pipe. Fuel-consumption figures obtained on furnaces making special muck bar for stay bolts, both with cold and preheated air, are given under "Results," p. 113. It may here be mentioned that with air preheated to 532° F. (280° C.) and with cold air 62° F. (17° C.) a reduction of about 10 per cent. in fuel consumption due to the hot-air supply is obtained. Melting times, &c., were as follows:

Period of operation, 4.30 A.M. to 2.38 P.M.

Total iron charged	**5028 lb.**
Total iron puddled	**4502 „ (4 heats of 1125 lb.)**
Loss of metal in furnace	**526 „**

Time of individual heats, 1 hour 50 minutes to 2 hours 15 minutes.

Some very valuable features of powdered-coal firing for puddling furnaces are evidenced by the records of gas analysis taken during the various operations. The charts (Fig. 25) show that perfect combustion, reducing, or oxidising conditions can be obtained at will, whereas with hand-firing such flexibility of control is impossible. These charts were specially made to find out from actual gas analysis the precise advantages in this direction which are directly attributable to powdered-coal firing as against hand-firing.

Fig. 26 shows a standard type of three-door heating furnace, fitted with waste-heat boiler and air-heating pipe. Furnaces of this design are generally used in America for heating iron piles, &c., and a number of such furnaces were seen in use for this purpose and for heating slabs for rolling.

Average charges for three-door furnaces serving 8 by 12 inches tandem mills were eighty pipe piles 4 inches by 4 inches by 24 inches. The average temperature of furnaces at commencement of drawing the charges was 2560° F. (1400° C.), the average times for the cycle of operations were: charging 9 minutes, heating 50 minutes, drawing 1 hour 15 minutes.

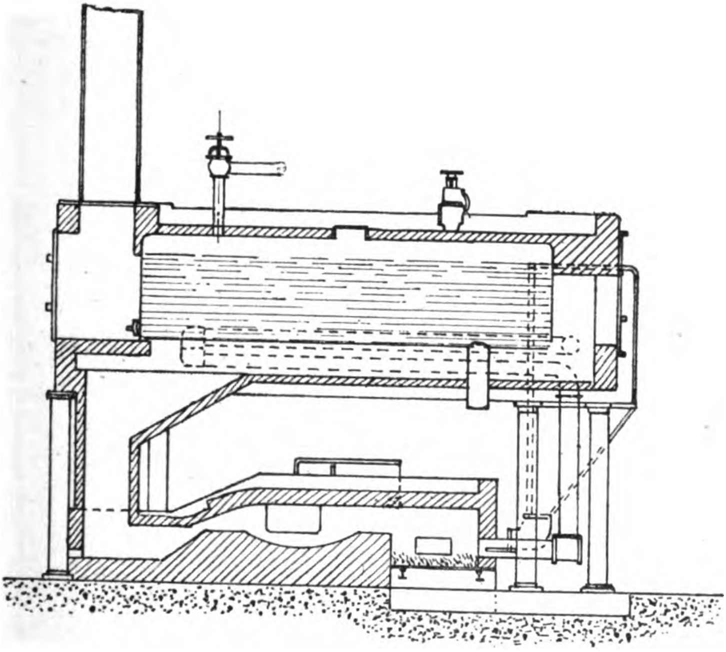

FIG. 24.—Powdered Coal Fired Puddling Furnace.

Blast-Furnaces.

In this connection the use of pulverised coal is not new, experiments having been carried out very many years ago with little success.

It is, however, interesting to quote verbatim a description

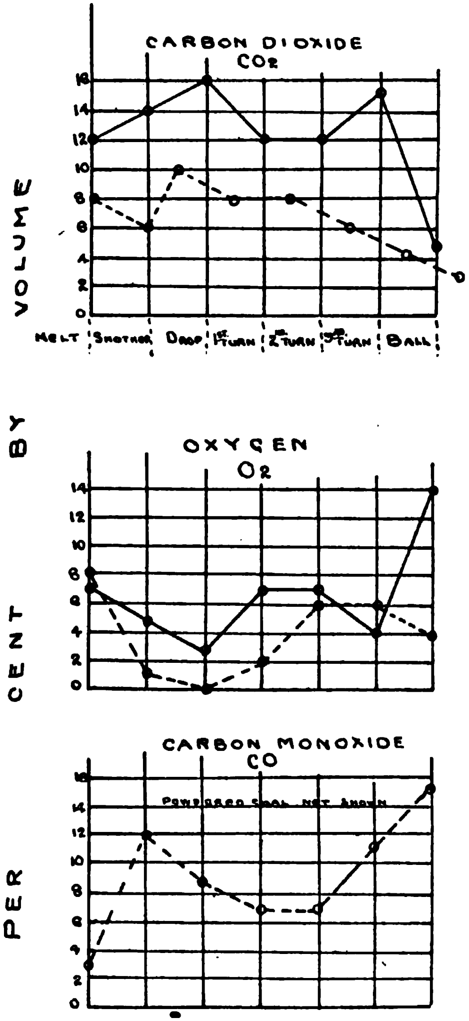

FIG. 25.—Puddling Furnaces. Flue Gas Analyses.

Powdered-coal firing ——

Hand-stoking - - -

of a recent report upon a proposed method of using coal for this purpose in Germany.

F. Lange[1] states that at the Phœnix Works at Kupferdreh from 4 to 8 per cent. by volume of lean and anthracite coal from a neighbouring mine was mixed with the iron-ore charge. This addition of raw coal was always found to have a good influence in the production of foundry iron, hæmatite, and ferrosilicon, and particularly on the silicon contents of metal. A similar addition is also to be recommended in the production of ferromanganese, especially when brown ore is used that contains the manganese as the higher oxide. Also the coke can be partly replaced by lump anthracite with a saving in cost depending on the prices of the materials.

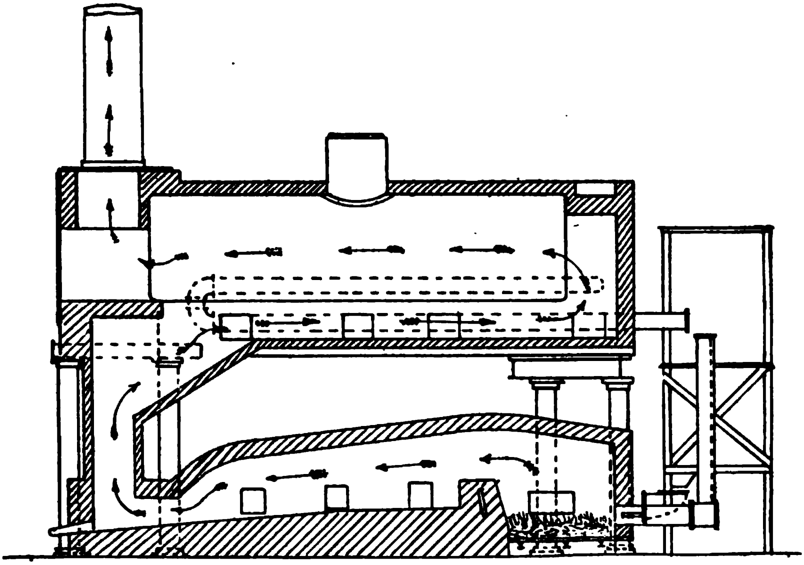

FIG. 26.—Powdered Coal Fired Slab Heating Furnace.

Another use of raw coal is its introduction through the tuyeres directly into the furnace, but in a dry and very finely powdered condition, so that not more than 16 per cent. remains behind on a 180-mesh screen. This use of raw coal is believed by Lange to have a good future. In order to introduce successfully a part of the fuel at the tuyeres it is absolutely necessary that a sudden and intensive combustion should take place, which can only be brought about by the greatest possible fineness of the coal. The temperature in the melting zone will be considerably increased, and the following advantages are to be expected:

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[1] *Stahl und Eisen*; *Iron Age*, 1915, September 2.

1. The cost for fuel will be smaller, because the coke is partly replaced by the much cheaper coal. At Kupferdreh if one-sixth of the coke were replaced by the dry-powdered coal the saving would be 1·25 marks per ton of pig iron.

2. The production of ferro-silicon, ferro-manganese, ferro-chrome, &c., will be made easier, and with ferro-manganese there will be less loss of manganese in the slag.

3. The top temperature will be lower, because less fuel will be added with the charge.

The influence of the fine coal may be compared with that of an increased blast temperature, because its effect is developed directly at the tuyeres. Its use is particularly recommended for small blast-furnaces, which are preferable when fine ores are to be used. On account of the heat developed by the coal the blast temperatures could be lowered so that the old pipe stoves would be preferable, on account of the regularity of temperature thereby obtained.

It is pointed out in conclusion that the powdered coal provides a suitable means of heating the stoves when starting up or when the gas supply is insufficient for any reason.

On this subject the author has received some valuable notes from Mr. Wotherspoon of New York, who kindly gives permission for reference to be made to this information.

Mr. Wotherspoon says that there is one important development in the use of pulverised coal of special interest, namely, the use of it in blast-furnaces for the smelting of non-ferrous ores.

A company has just been formed in New York to work patents covering the processes of smelting by pulverised fuel. The novelty is the combustion of pulverised fuel under pressure in the restricted combustion space contained in a blast-furnace charge, which space consists of the voids in the charge, that is, in the ores, fluxes, and by-products, and in the channelling in the smelting zone.

At Tennessee a furnace has been operating for some time with all the coke replaced by pulverised coal, and it has been found that the percentage of powdered coal required is 3·8 per cent. as against 6 per cent. or more of coke in ordinary practice, thus showing not only very important economies due to the substitution of a cheap fuel for an expensive one, but also a reduction of about 30 per cent. in tonnage required.

At the International Nickel Company's smelter works extended runs have also been made with the coke reduced to one-half, with the deficiency in fuel made up by pulverised coal.

Nodulising Iron Ore.

Iron ore is nodulised in kilns of similar design to those used for burning cement; the high temperature produced by combustion of coal dust renders this method of heating very successful for nodulising iron ore, in which form it can be charged into blast-furnaces with a minimum of loss.

Boilers.

This subject has been fully treated in the Report submitted to the Director of Fuel Research, but it will not be out of place to record here the views of Professor W. F. Durnand,[1] Leland Stanford University, California:

"To obtain the best results in the furnace the coal should be ground to a degree of fineness which will insure the passage of 95 per cent. through a 100-mesh screen and 85 per cent. through a 200-mesh screen.

"With coal thus prepared and with heating value 11,580 B.t.u., tests have shown an equivalent evaporation of 8·38 lb. per pound of coal fired and of 10·9 lb. per pound of combustible. With Texas lignite with a heating value of 11,250 B.t.u. the results showed 7·26 lb. per pound of coal fired and 8·81 per pound of combustible."

These remarks were made in relation to the possibility of firing boilers with Texas lignite carrying as high as 20 per cent. ash and 30 per cent. moisture, and the results are indicative of what can be accomplished with low-grade fuels for this purpose.

In connection with copper-smelting furnaces, waste-heat boilers are invariably used, and it has been stated that, as compared with hand-fired furnaces, boiler tubes are cleaned no oftener when using pulverised coal than for hand-firing. The ash in the waste gases gives very little trouble, flue connections being cleaned out once a day. With certain coals less trouble has been experienced in cleaning away the ash in flues with a 20 per cent. ash coal than with a coal containing only 9 per cent. of ash but of a more fusible nature. Approximately 50 per cent. of the total ash content remains in the furnace and is run off in the slag.

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[1] *Electrical World*, January 6, 1917.

An illustration in the "Report" shows the arrangement of a Dutch oven built out in front of the boiler and the provision of slag chamber that is to be preferred in cases where an ash-pit of the design shown can be used. It is essential to provide a sufficient combustion area per pound of coal burned per minute or per hour, otherwise incomplete combustion results, and ash is not deposited in the slag chamber in the quantity required. An undesirable deposit will also be found on the boiler tubes, due to the partly burned particles of coal adhering to the tubes and fluxing thereon, and to the high velocity of gases through the restricted combustion chamber. This results in the carrying over of an undue proportion of the ash.

With correct combustion space and low velocity of gases readily fusible ash is deposited in the slag chamber, and the fine more or less infusible particles float through the boiler tubes and boiler passes.

In cases where it is impossible to excavate under the boiler setting to provide for the slag chamber, or for the ash tunnel, an extended Dutch oven must be employed to obtain the required minimum combustion area.

The ideal conditions exist, of course, when a new plant is to be designed. Fig. 27 shows the latest approved arrangement. All burner and air-supply piping is out of the way in the ash tunnel, and ample provision can be allowed for the ready handling of the slag deposit and fine dust removal.

Applications to Lancashire boilers are not so easily carried out when space in front of the boiler is limited. A suitable arrangement, having in mind the essential points mentioned above, would be that shown in Fig. 28.

The ideal arrangement would be to have a deep and narrow

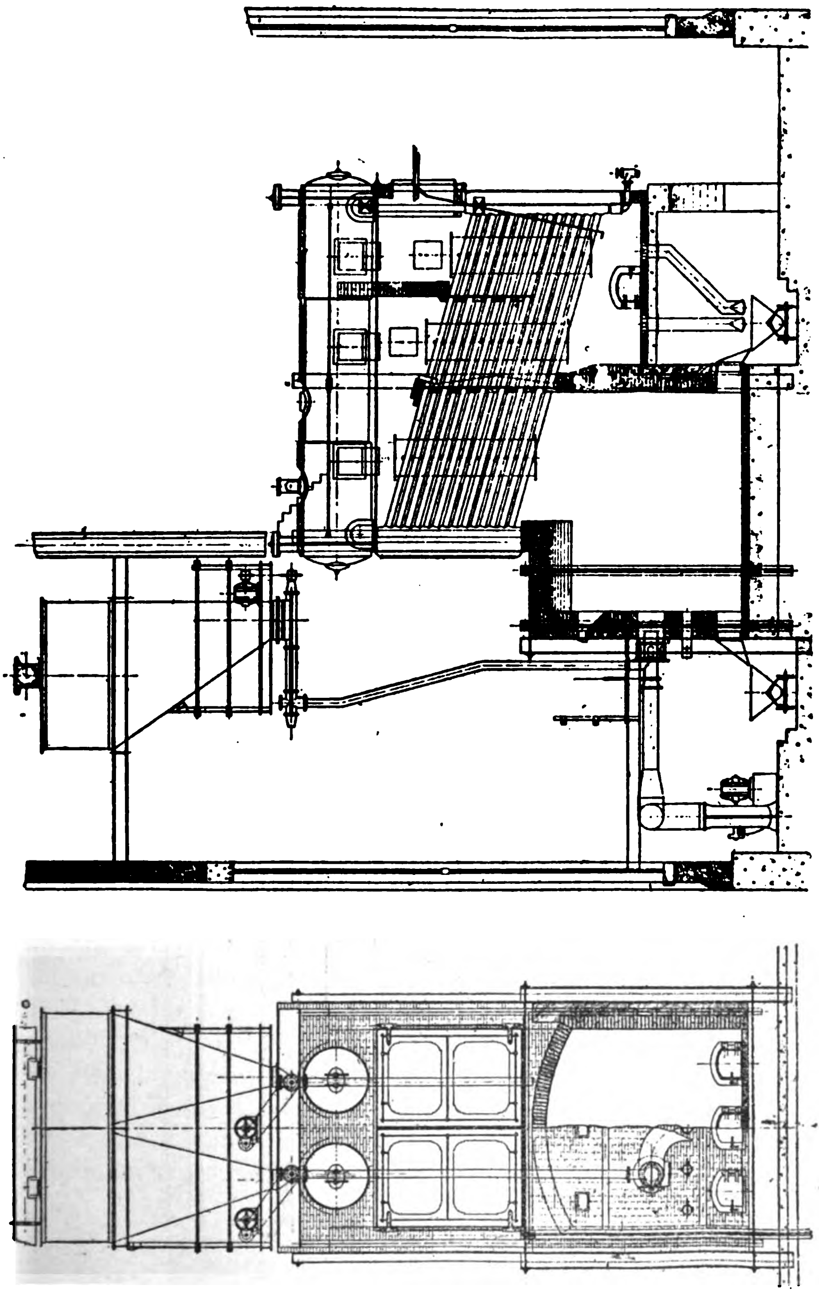

FIG. 27.—500 H.P. Babcock & Wilcox Boiler, Arranged to be Fired with Pulverised Coal.

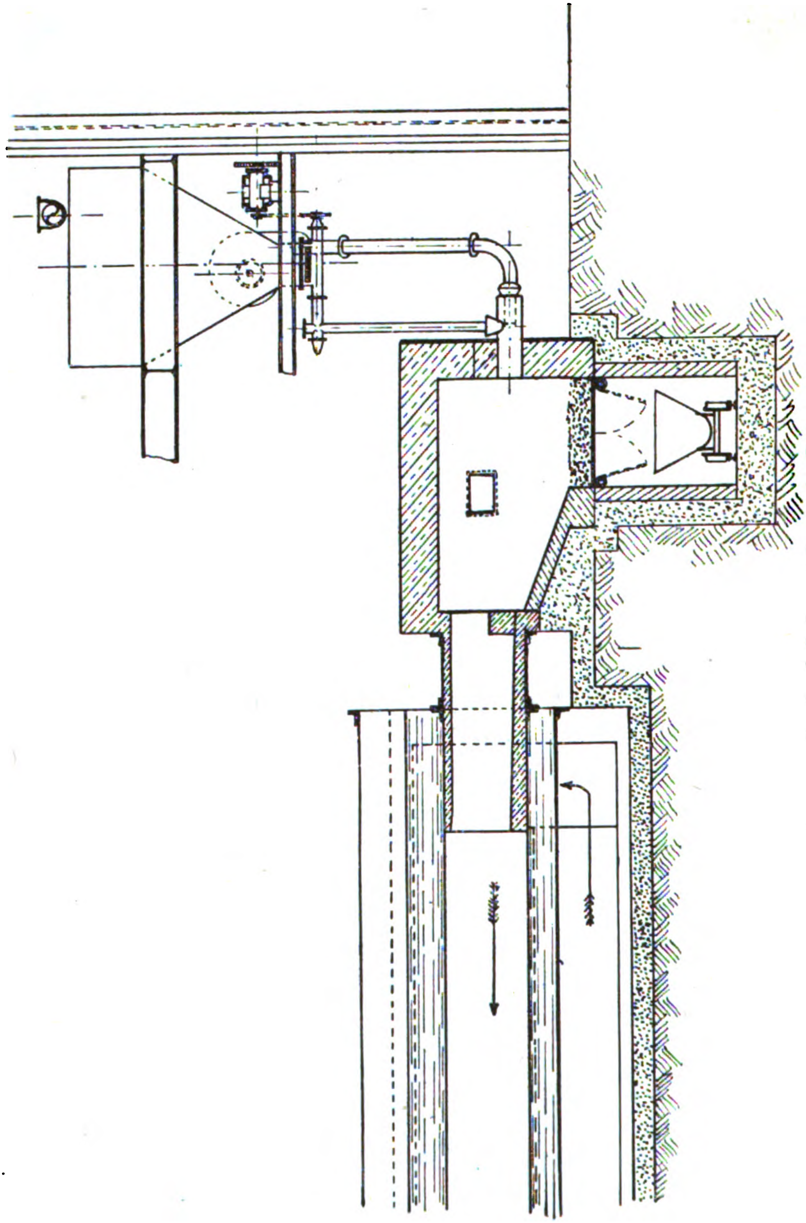

Fig. 28.—Powdered Coal Fired Lancashire Boiler.

combustion chamber in front of the boiler with a burner at each end, but Lancashire settings are as a rule so close that this method cannot be adopted.

Waste-Heat Boilers.

The application of powdered fuel to high-temperature furnaces, open-hearth melting, puddling, forging and welding, billet-heating furnaces, with the exception of those of the continuous type, and cement kilns makes it possible to instal waste-heat boilers with great advantage. The temperature variation in such furnaces is very small, comparing favourably in this respect with the uniform temperatures obtainable with gas and oil firing. The fine unfused ash dust passing into the boiler from the furnace causes very little inconvenience.

The utilisation of waste heat from metallurgical furnaces was very fully dealt with by T. B. Mackenzie [1] at the last meeting of the Institute, and heat balance-sheets and results of tests will be found in his paper. A. D. Pratt [2] has also recorded the results of tests of waste-heat boilers attached to open-hearth furnaces.

By the use of a supplementary burner fitted at the uptake to the boiler, steady steaming at full rated output can be obtained, thus removing the usual objection to this type of steam supply plant.

Locomotives.

The work that must be carried out in order to convert hand-fired locomotives to powdered-coal firing is not excessive, and the equipment is not at all complicated; for instance, the Fuller apparatus has been designed with reliability and simplicity as the two outstanding features. For this system, as a rule, standard brick arches are used. The burners are made as large as possible, so that velocity of the entering coal-dust mixture is low, which eliminates a cutting flame and damage to the refractory brickwork. The two screw feeders are geared to a slow-speed, two-cylinder reciprocating engine. Either burner can be used for maximum feed should this be necessary. The feeder engine can be

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[1] *Journal of the Iron and Steel Institute*, 1918, No. II. p. 139.

[2] *Journal of the American Society of Mechanical Engineers*, December 6, 1916.

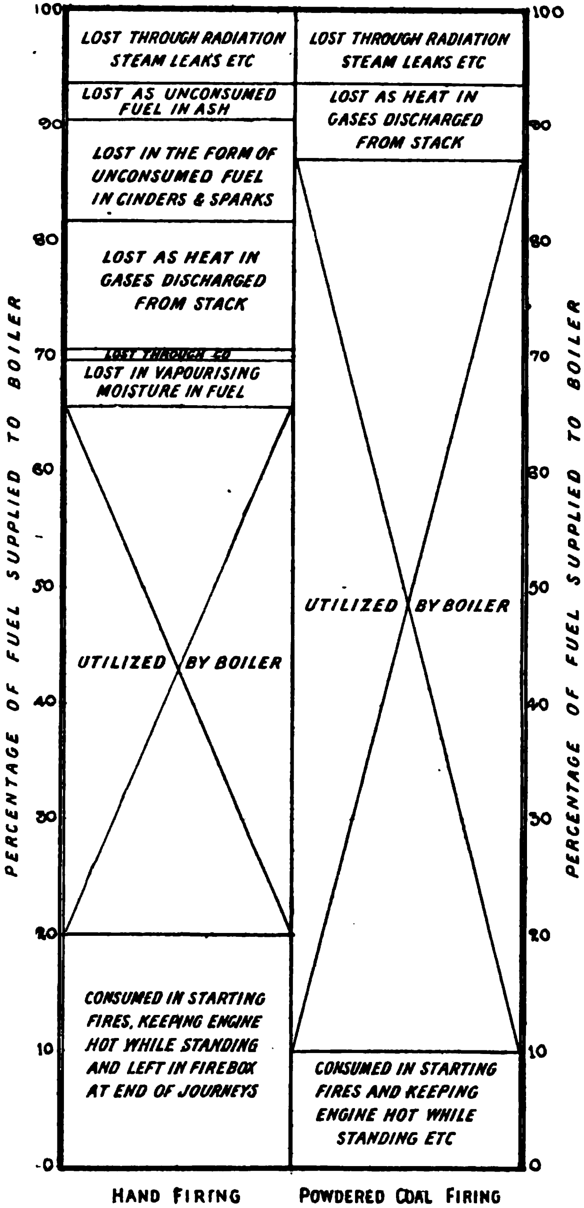

FIG. 29.—Comparison of Approximate Utilisation and Waste of Fuel supplied to a Locomotive Boiler with Hand and Powdered Coal Firing, taking Fuel as delivered to Engine Tender.

run off the round house steam supply until 15 lb. loco boiler pressure is developed and will run under all pressures from 15 lb. to 200 lb. per square inch. Three hundred per cent. feed regulation can be effected from the cab control and 600 per cent. by shifting over the gear-control lever. A steam turbine fan is used to supply air at 2-inch (w.g.) pressure.

The application of pulverised coal to colliery locomotives should be of considerable value, thereby rendering possible the burning of low-grade coals, which may be unsuitable for sale as commercial fuel.

It can be taken that at least 20 per cent. to 30 per cent. of coal tonnage now required for hand-fired locomotives can be saved.

Diagram Fig. 29 shows a comparison of the fuel losses in locomotive boilers, when hand-fired and when using powdered fuel.

Marine Propulsion and Internal-Combustion Engines.

Reference to the trials conducted on U.S. scout patrol ship *Gem* with powdered coal has been made in the "Report." During these trials it was demonstrated that equal speed could be obtained with steam generated in one boiler fired with powdered coal as with two oil-fired boilers. At the same time a CO_2 content of 14–16 per cent. was maintained when using coal dust.

There is an extremely important field for investigation in this direction, and it may eventually become possible to pulverise and use ordinary bunker lump coal without having to rely upon shore pulverisation and the bunkering of coal in powdered form.

Very successful trials have been run over extended periods on a cruiser under war conditions during the past two years, one boiler having been fired almost exclusively with powdered coal.

Another question now receiving attention is the supply of powdered coal and air as an explosive mixture for internal-combustion engines. Much work has been done already in America, and difficulties with deposit and cutting of engine valves have been to a very great extent overcome. This method of power development is destined to become of increasing value in the future.

LIGNITE, PITCH, AND COLLOIDAL OIL AS FUELS FOR METALLURGICAL PROCESSES.

Lignite.

Lignites are soft and readily ground, so that mill output is increased as compared with the rates for grinding anthracite or bituminous coals; power per ton ground is correspondingly reduced. Apart from the necessity of drying slowly, owing to the heavy moisture content which reduces the capacity of dryers, lignite is an excellent fuel where sulphur contamination is to be avoided, for it contains little or no sulphur as a rule, and the more or less infusible ash is easily removed from combustion chambers or flues.

The following is an account by Mr. W. H. Maddocks, of the M.K. and T. Railway, regarding the first tests ever made with powdered lignite for firing boilers. The tests were run on some of the O'Brien boilers fitted with Fuller Engineering Company's equipment. "Hoyt, Texas, lignite as tested gave the following analysis:

	Wet. Per Cent.	Dry. Per Cent.
Moisture	24·48	7·06
Volatile	38·17	54·52
Carbon	28·94	24·72
Ash	8·41	13·70
	100·00	100·00
Sulphur separately determined . .	0·53	0·098
B.t.u.	7996	10675

"Five car-loads of this coal have been used under various conditions. Two of them had been exposed to heavy rains and showed 46 per cent. moisture. With our limited dryer capacity the coal was repassed and when finally used showed moisture varying from 7 to 13 per cent. Coal burned under these conditions gave good results, no slag, and under high forcing of the furnace an evaporation of 7·33 to 8·8 lb. from and at 212° per pound has been obtained with this low B.t.u. value. No choking of screens occurred in milling at this moisture content, but it is believed the limit was about reached.

"The average fineness was 93 to 94 per cent. through 100-mesh and 84 to 86 per cent. through 200-mesh screen; this with a moisture of 7 per cent., not quite so good with 13 per cent.

moisture. Quantity milled was in excess of bituminous coal. One car was unloaded in November 1916 and the coal was stocked and used the following summer. This was dried, milled, and used with no appreciable loss.

"With a dryer designed for this coal with its excess of moisture it could be burned equally as well as bituminous and with less deterioration on furnace refractories due to non-slagging."

Pitch.

Pitch as a fuel has valuable characteristics and is burned in a liquid state in the manner described in the "Report."

It can also be burned as a pulverised fuel; for obtaining this in powdered form special mills must be used, and only hard pitch having high melting points can be successfully treated in this manner. An analysis of hard pitch shows [1] that its calorific value can be as high as 15,928 B.t.u. per lb., moisture 0·05 per cent., ash 0·60 per cent., volatile matter 66·85 per cent., fixed carbon 32·55 per cent. It contains no sulphur, and is, to all intents and purposes, free from ash. It requires no drying, and can be successfully pulverised if its melting point in air is above 150° C. By means of centrifugal force, pitch can be reduced to shot of any size, and this process is more readily accomplished than direct pulverisation.

Pitch is an ideal fuel for special high-heat work when completely burned, and this can best be effected when applied in shot or powdered form.

RESULTS.

Typical Results obtainable on Metallurgical Furnaces using Pulverised Coal.

Annealing Furnaces (Malleable Iron Castings).	Hand-Firing.	Powdered Coal.	
Coal per ton of castings	880 lb.	340 lb.	61 per cent. Saving.
Castings annealed per 1 lb. of coal	2·25	5·8	
Cost of annealing pots per ton of castings	$2·25	$0·83	63 per cent.

The above results for annealing furnaces were given by a user for furnaces prior to and after conversion to powdered coal and with the same quality of fuel.

Power, June 25, 1918.

Heating Furnaces for Forging Presses.	Hand-Firing.	Powdered Coal.
Furnace running	537 hours	537 hours
„ heating up	88 „	88 „
Total steel heated in the two furnaces	3238 net tons.	
Total coal used	373·16 gross tons	200·18 gross tons
Lb. coal per ton steel heated	515 lb.	277 lb.

Shell-Heating Furnaces.	Hand-Firing (2 Furnaces). 12-Inch Shells, 1060 Lb.	Powdered Coal (1 Furnace). 12-Inch Shells, 1060 Lb.
Shells heated	5174	4505
Total steel heated, tons (2240 lb.)	2449	2132
Total coal used	726630	343275
Lb. coal per ton steel	296	161

Open-hearth furnace:

500 lb. per ton of steel as against 800 lb., with gas-producers using the same grade coal and for the same composition of steel.

Performance of open-hearth furnace, June 13, 17, 1916:

Heat No.	Time. Hrs. Mins.	Tons Ingots.	Pulverised Coal per Ton Ingots.	Total Coal per Ton Ingots.	Pulverised Coal per Hour.
3327	9 40	39·913	661	685	2730
3328	10 15	49·554	542	561	2620
3329	10 55	47·764	558	578	2440
3330	10 20	46·929	539 (average)	558 (average)	2615
3331	9 10	47·571			
3332	9 20	45·475	550	569	2710

Puddling furnaces:

Hand-fired, 2200 to 3300 lb. per ton of iron.

Pulverised coal, 1200 lb. to 1600 lb. per ton of iron. Summer months, 2 turns.

Air preheated 500° F.

Average coal consumption 1230 lb. per ton of iron operating in cooler months on 3 turns.

Heating furnaces:

Hand-fired, 900 lb. per ton of iron reheated.

Pulverised coal, 550 lb.

For 12-inch rolling-mill. Average, 535 lb. coal per gross ton steel for 16-inch rolling-mill. 518 lb. coal per gross ton steel.

Continuous heating furnace:

Steel billets 5 inches by 7 inches by 14 feet long.

Hand-firing, 220 lb. per ton.

Pulverised coal, 168 lb. per ton.

Bushelling furnace for 16-inch mill:

Average 542 lb. coal per gross ton steel.

Fagotting furnace for 16-inch mill:

Average 530 lb. coal per gross ton steel.

Medium forge furnaces:

When heating blooms 10 inches thick by 18 inches wide and 15 feet long, the coal consumption with hand-firing was 650 lb. per hour, and with pulverised coal 350 lb., and at the same time the furnaces gave a 20 per cent. increased output when fired with powdered coal.

Furnace for wrought iron welding:

Pipe skelp heated by means of pulverised coal of 14,000 B.t.u. value, 275 to 300 lb. per gross ton of iron welded.

Furnace for heating wrought iron:

Muck bar piles, 640 to 720 lb. of coal per gross ton of bar produced.

Ore Smelting.

Zinc-copper ore in reverberatory furnaces.

Hand-firing, 40–50 tons of coal used for smelting 30 tons of ore—say 150 per cent. fuel consumption.

Powdered-coal firing, 30 tons of coal used for smelting 90 tons of ore—33⅓ per cent. coal consumption.

Saving 116 tons of fuel per ton of ore smelted.

Colloidal Oil.

This fuel is a product of the war, and original experiments in its manufacture and application having proved a success, it is quite likely that it will find a place amongst commercial fuels of the future.

Owing to the high price and relative scarcity of oil supplies, experiments were taken in hand by Mr. Lindon W. Bates, Chairman of the Engineering Committee of the Submarine Defence Association of America, to produce a satisfactory substitute fuel which would at all events economise in the consumption of oil.

Colloidal oil, a mixture of approximately 70 per cent. straight fuel oil and 30 per cent. powdered coal, having a calorific value per equal volume corresponding to the original oil used, has been the outcome of these experiments.

The difficulty of maintaining the powdered coal in suspension has been overcome by the incorporation of a certain fixative which effects the combination of the coal dust and oil to a great extent in a colloidal state, so that very little free carbon is deposited by settlement when once the colloidal mixture has been made.

Satisfactory tests were carried out on the U.S. patrol ship *Gem* as a parallel test to that of using powdered coal.

As a fuel for metallurgical work it has possibilities, for it is stated that opinion in America amongst steel melters is that fuels for this purpose are preferred in the following order:

Natural gas.
Producer-gas.
Fuel oil.
Powdered coal.
Tar.

By saving 30 per cent. of expensive fuel oil and replacing this with powdered coal plus the fixative which maintains the coal dust in chemical combination with the oil and also raises the calorific value of the mixture to that of the straight oil used, considerable economy in freightage and tanker capacity will result.

The fuel can be applied in the same manner as for fuel oil and without any change of burners or combustion areas.

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DISCUSSION.

Mr. B. Talbot, Member of Council, said the paper frankly meant reverting to the use of raw coal for some of the chief operations in the manufacture of iron and steel. If what was said by economic experts was correct, raw coal would not be allowed to be used in the future, because of the by-products which would be lost if any such system as that under discussion came into general use. He did not wish to disparage such a development as that discussed in Mr. Harvey's paper, but he thought the suggestion to revert to raw coal for open-hearth furnaces might in the end prove a retrograde step. What was useful and easy to apply in the diversified operations ensuing after an ingot had been made was another matter. Ordinary common steels were made, practically, from the liquid iron of the blast-furnace, and that being so, obviously coke was absolutely necessary, and should be the only fuel used as far as the manufacture of the ingot was concerned. Mr. Harvey said it was immaterial what the quality of the coal might be. If that were true it was about the only exception to the general rule that he knew of. Unfortunately coal was now being supplied which in pre-war days manufacturers would not have looked at. The ash was beyond all reasonable limit. If that continued, many large iron and steel works would be forced to put up elaborate washing plants. Whether the coal was going to be used in the coke-oven, or whether it was going to be used in the gas-producer—which he hoped it would not be—or even if Mr. Harvey's system was to be introduced, he (Mr. Talbot) believed that in the end the ash would have to be washed out unless the quality reverted to that of pre-war days. He thought members ought to thank their friends in America for such an interesting development. He would like to ask whether the system was being used in combined plants such as Gary, which, as was known, had large coke-oven plants and blast-furnaces, and was using its surplus gas for various operations.

Mr. G. Carrington, Hon. Member of Council, inquired what effect the system described would have on wrought iron, the product of puddling, and on the iron piles in reheating furnaces. Those two points were most material. As Mr. Talbot had also pointed out, the coal which was being supplied to-day would not have been looked at prior to the war by manufacturers, despite the fact that they were paying three or four times as much for it. He feared, however, that the quality would continue to deteriorate. That being so, the ash from the coal became a very serious question, and if, as it passed through the furnace—and he failed to see how the spent gases could pass through the furnace without carrying some ash—that ash were dropped on the product, he would like to know what effect it would have, and what percentage would get generally mixed up with the products of, say, a reheating furnace and a puddling furnace.

In the Midlands the ash was of a heavy limey nature, more liable to drop into the product, and if mixed with, say, puddled iron it would be very difficult, if not impossible, to slag it away, while if it were retained it would cause trouble and laminations in the finished iron.

Professor H. Louis, Member of Council, asked whether it was absolutely necessary that the coal should be freshly ground or whether it made any difference whether the coal had been exposed to the air and to some extent oxidised. If it were possible to use coal-dust which was not freshly ground, the paper opened up very great possibilities from a point of view which the author did not seem to have thought of. He referred to what he might call natural coal-dust. Everybody knew that in coal-mining more or less dust was, unfortunately, always made. He could instance some South Wales mines, in which the coal was rather brittle and dusty, where enormous quantities of coal-dust were made. He had been in some heapsteads in South Wales where he had walked ankle deep in coal-dust. Coal-dust was a deadly enemy in the pits, and all the big colliery explosions had been due to its presence. The present method of reducing the coal-dust danger was by stone-dusting—namely, mixing stone-dust with the coal-dust, and from time to time tramming out the mixture. It was perfectly possible by systems of dry blowing which had been used for years on a working scale—he did not mean experimentally, but year in and year out, on a big scale—to separate coal-dust from stone-dust and to get finely divided and very pure coal-dust exceedingly cheaply. Obviously if it were possible to use such coal-dust in the way indicated by the author, it opened up a very interesting vista to the coal-miner. It showed him the possibility of utilising economically and turning into money that which hitherto had been at its best a very great nuisance, and at its worst the deadliest source of danger against which the coal-miner had to fight. If the author could show how to make that into a commercial proposition, he would have done a very great deal, not only from the economic point of view, but from the point of view which he (Professor Louis), like many others, looked upon as the most important in coal-mining, namely the saving of the miners' lives.

Mr. H. M. Ridge (London) said the subject was an extremely interesting one, and one which he firmly believed might lead to appreciable economies in fuel consumption both in smelting steel and non-ferrous metals; but he wished to emphasise the absolute necessity, already mentioned, of eliminating the impurities in the coal-dust to be used for firing. Heating efficiency curves showed extraordinary results when comparing fuel of different composition and the flame temperature was rapidly reduced with increasing ash content. As an example he would mention the use of non-combustible dust by the coal-miner as a means of preventing the spread of a colliery explosion. Using powdered coal very high in ash was really doing something similar; the ash reduces the temperature, reduces efficiency, and in an extreme case could extinguish the flame; at the same time it added an undesirable impurity which not only affected the composition of the product from the furnace, but which was also going seriously to affect the life of the refractories used. That was an aspect which had to be considered. On the Continent there were huge coal washeries laid out on an elaborate scale. If powdered coal were to be used, and if the coal were to be supplied to the smelting works as high in ash, as was being done to-day and as had been done during the war, it would necessitate further steps being taken at enormous expense, because the user would have to separate the ash. Doing that, during combustion, in a furnace was most wasteful.

Mr. J. H. Harrison, Hon. Member of Council, asked whether the Report referred to in the paper had been published, as he had been unable to get a copy.[1] The paper was most valuable and was also new, and although he agreed with Mr. Talbot that it might be a retrograde step in one sense, there were many works where the process described could be made valuable use of, and where there were no blast-furnaces in connection with the steelworks or ironworks. The utilisation of coal which was in other respects of very little value, in the way suggested, might very well have important advantages.

Dr. W. H. Hatfield (Sheffield) said several speakers had suggested that the method was new; but he was over in the States in 1908 and was impressed by the apparent efficiency of reheating and annealing furnaces worked on the plan described. The powdered coal seemed to be quite successful. Of course there was the cost of the preparation of the coal to place against the 25 per cent. loss of energy on conversion of the coal to gas, and there was also the question of the interference of the ashes in metallurgical processes. Personally he had not had the opportunity of comparing practically the two processes, but he would suggest that as eleven years had elapsed since 1908, when the process was in commercial operation in the United States, it would be extremely instructive and very much to the point if the author could give the extent of the commercial application, the number of plants and furnaces where the system had been taken up, and show the gradual increments in plant in any particular line. Members would thus obtain an actual practical demonstration of what had been found to be economical. If some practical information of that kind could be given it would be very valuable.

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[1] The Report in question was issued the day the above discussion was held. It is published for the Department of Scientific and Industrial Research by His Majesty's Stationery Office, the price being 2s. 6d.

Mr. H. H. **Hayes** (Birmingham) asked whether powdered coal would be applicable to the ordinary annealing furnaces in the non-ferrous metal industry. Such furnaces were about 30 to 40 feet long and 10 to 20 feet wide, with a honeycombed arch. It seemed to him that the application of powdered coal would enable temperatures to be controlled more easily than with ordinary hand-fired coal.

Mr. F. W. **Harbord**, C.B.E., Member of Council, thought everyone would agree with Mr. Talbot that in any modern well-balanced plant, the ideal thing was not only to generate all the power required from gas, but also to do all the heating required, either from the blast-furnaces or from the coke-oven gases; but to-day the majority of plants were not so balanced, and many works had no blast-furnace or coke-oven plants, and consequently it was a question of gas-producers *versus* some other method of heating the furnace. There could be no question that, assuming the heat of the coal could be generated by the direct combustion of coal-dust where it was wanted, it would be much more economical than producing gas in a gas-producer, where a large quantity of fuel was used in converting it into gas, and then utilising the gas in the furnaces. The efficiency of the method described, therefore, was to be compared, not with a plant where there were available supplies of gas, but with a similar plant which had to rely on gas-producers. It was well known that in cement burning it was much more efficient to use coal-dust than gas, and coal-dust had been used for that purpose for years. Mr. Harvey spoke about the screw feed. His (Mr. Harbord's) own experience was that unless a screw feed was fed practically at about half its capacity, there was a great danger of the fuel jamming. Had any difficulty of that kind been experienced? It was a very important matter, because if the feed was not maintained regularly the heating results would be irregular. With regard to slag, he did not believe for a moment that it was possible to use impure coal to do efficient work in the open-hearth furnace. If a high ash coal could be used, it would give a low efficiency and there would be great difficulties with the slag; the ash would either go into the slag bath or into the checkers or into the flues, and in either case it would lead to serious trouble.

Mr. J. E. **Fletcher** (Dudley) wished to call attention to the use of powdered fuel in puddling furnaces. Dr. Hatfield had already mentioned that the proposal was scarcely a new one. Considering the difficulty that was being found to-day with labour in puddling, many people were looking forward to mechanical puddling again, and he remembered that a good many years ago Crampton used powdered fuel in a mechanical puddling furnace. On Fig. 25 in the paper three diagrams were given which were very enlightening, as they pointed to the possible elasticity of the method in a puddling furnace, and showed that the atmosphere could be controlled, which was a very vital question in getting high yield. Was the use of powdered fuel in puddling in America really general, and if so was it uniformly successful? Another point raised was in connection with the impurity of the coal used for the method. There were various fuels used, especially in the Black Country, where there was very often fuel which was high in limey ash. In such cases considerable inefficiency might arise through temperature inefficiency due to a high ash containing large percentages of lime (as carbonate).

Sir **William Beardmore**, Bart., Past-President, thought there were many arguments both in favour and against adopting the process. Some months ago he had a considerable amount of data put before him, collected by one or two firms in America who had been using the process for the last three or four years, and he became so interested in the information given him that he decided to put down an experimental plant and test the process at his works in Scotland. That plant was now being built and he hoped would be at work in the next two or three months. When he had the results of the experiments he would be very pleased to place them at the disposal of the members of the Institute.

Mr. W. **Savage** (Crewe) asked the author whether he could give the relative cost of using coal-dust as against the cost of gas-making.

Mr. E. B. **Christmas** (Sheffield) said that, being greatly interested in the subject, he had taken the opportunity of writing to America to a firm that was not interested in the question of what fuel was used, and the reply was as follows:

" We would advise that a great deal of time and money has been expended in this country in an effort to make pulverised coal a successful fuel for open-hearth steel furnaces. It is used with satisfactory results in rotary cement kilns and for a few other special purposes, but the consensus of opinion amongst steelwork operators is that it cannot be successfully applied to regenerative furnaces, and in almost every case where it has been attempted the installation has been abandoned. You cannot use checkers in regenerators, as they clog up at once with the ash, and not enough heat surface can be secured from brick pillars or piers built in the chambers. The only fuels that are successfully competing with producer-gas are natural gas, oil, coke-oven gas, and tar. The price of oil is so variable that no plant is certain that they can afford to use it for any considerable period. Coke-oven gas and tar are ideal when available, but usually this fuel can be used to better advantage in heating furnaces around a steel mill, with the result that there is seldom enough left for the open-hearth furnaces."

There was another point that did not seem to have struck previous speakers. If the fuel could be carried with a few inches of water pressure to the furnace, how could it be stopped from getting into the furnace? Here was a fuel which was ground so finely that it had become so light that it could be easily carried through small diameter pipes, and therefore around bends in those pipes under an exceedingly low pressure. The fuel, and therefore the ash in that fuel, was so light that it would not drop, or stop, in such small diameter tubing but would continue on its way until it reached the burners at the furnace. Any furnace to work successfully would have to have a suction from its stack apparently much greater than the pressure required to deliver the fuel to the burners. How then could such light fuel be prevented from entering the furnace simply by letting it first enter some chamber comprising baffle walls. Why should it not continue on its way, sucked in by the stack?

Some of the dust would fall into the dust pocket owing to the change in direction caused by the baffle walls, but as far as he (Mr. Christmas) could see a lot of the dust, or ash, would continue onward into the furnace and then either mix with the material in the furnace, or be caught in the flues, or in the regenerators on the exit side of the furnace, or be spread about the locality in the form of a light powder from the top of the stack. If the latter result took place, a firm which employed the method extensively, and therefore used thousands of tons of coal per annum, would become a nuisance to their neighbours, or would, at least, cover everything in their own works with dust.

Mr. A. HUTCHINSON (Saltburn-by-the-Sea) said Mr. Talbot had practically covered the lines of any criticism he could make; but he was strongly of opinion that if the coal could be successfully washed at a works consisting of a combined blast-furnace and steel plant, and if, from that coal, any coke-oven by-products could be obtained and the residual gas used for the operation of the plant, it would be the most economical use of the fuel. It seemed to him that to go back to the consumption of the whole of the fuel in a powdered state would be a retrograde step. He could understand that at works to which no blast-furnaces were attached, there might be certain applications in which powdered fuel might be of great advantage; but he thought a condition was being arrived at when everything would have to be brought together as nearly as possible, and the steel furnaces would be where the blast-furnaces were. Besides that, manufacturers might be compelled to get out all the products before they were allowed to use the coal in the way that had been suggested.

Mr. L. C. HARVEY (London), in reply, said the answer to the question of whether coal should be used at all in powdered form did not lie with him or with people who were advocating powdered coal plants, but it certainly would be very many years before the national superpower generating stations, in which was going to be incorporated a low temperature distillation of fuel, covered the whole country. When it was possible to make use of all the by-products of fuel and obtain the gas and convert the power into electricity, it might be possible to prohibit the burning of fuel directly in a furnace; but that time, he thought, was a long way off, and in the meantime there was a prospect of saving up to 50 per cent. in fuel consumption in many of the metallurgical furnaces, especially puddling furnaces. In America there were a number of powdered-coal fired puddling furnaces—he knew of thirty in one installation—and when he was over there the previous year there was a project for equipping eighty puddling furnaces in one shop; but the process was held up for twelve months or more pending the result of investigations into a new process of mechanical puddling. The question was thoroughly considered, and ultimately it was decided that mechanical puddling could not yet be successfully accomplished, and that being so the firm was ready to go ahead with applying powdered coal to the works. The overall annual saving in money, in fuel, and in extra output of the furnaces, meant something like £60,000 or £80,000. Much of the information required to answer questions raised by speakers was contained in his special report to the Fuel Research Board. There were many pages dealing with results and practice in the metallurgical industry, and actual opinions of users were given. Each subject was fully treated therein, and taking for instance the question of open-hearth steel smelting furnaces, the Report started with the "Advantages Claimed," "Range of Fuels Available," and "Disposal of Ash and Slag." After that came the opinions of users. Referring to puddling furnaces and the advantages claimed, the Report stated: "Pulverised coal has introduced a method of heating by which the puddled iron can be worked up by the puddler with uniformity and speed, the output of furnaces being a maximum when compared with any other method of firing that has been tried out in some of the American works." On the question of the disposal of the ash and slag the Report stated: "From 60 per cent. to 70 per cent. of the ash contained in the coal should be thrown down in a semi- or completely fused state in the combustion chamber, arranged in a manner similar to that in piling furnaces." Each puddling furnace had a free combustion chamber in which most of the ash would be collected, and probably there would not be more than 10 per cent. of the total quantity of ash actually deposited on the surface of the metal in any furnace. Ash that was not fused in the combustion chambers was in such a fine state that it passed right through the furnaces, and, in open-hearth furnaces, into the checkers, and that was the reason why open-hearth furnaces, of which he gave a diagram, should be fitted with removable slag bogies below the down take flues. That was a design of furnace that was now recommended

It was preferable to design an open-hearth furnace for use with powdered coal, for adequate provision could then be made for collection of the ash; but if an existing gas-fired open-hearth furnace having small passages through the checkers was going to be converted, then the troubles which had been experienced in America would be repeated in this country. In such instances the first few courses of the checker work would become clogged up with ash and would have to be cleaned out, and probably renewed after some 200 heats. The particular furnace illustrated, fitted with removable ash bogies, could be run for 300 to 400 heats before it became necessary to clear out the checkers. It was hoped that 500 to 600 heats would be obtained, which would then equal average practice for producer-gas firing. In that way the trouble with ash deposit in open-hearth furnaces could be overcome. Any grade of carbonaceous fuel could be pulverised and burned. Whether it was going to pay to use a coal containing 30 per cent. of ash depended upon what other fuel could be obtained of a higher grade. It was naturally uneconomical to pulverise 30 per cent. of inert material because of the power that was going to be used in doing useless work; but where low grade fuels existed and it was difficult to obtain supplies of better quality coal, it was certainly the best way to make use of otherwise useless material. Brazil had been running powdered coal locomotives for nearly two years, and prior to the application it was necessary to import either British or American coal for use on the railways. In Brazil they had large deposits of inferior coal which they had never been able to use on either hand-fired grates or mechanical stokers, but were now getting excellent results from in the powdered form. If statements he received from America were correct, they were going to run 250 engines using powdered local fuel on the Brazil railways, which meant that they were going to use their natural resources instead of having to import expensive coal from England or from America. In Sweden also they were now running locomotives on a mixture of pulverised peat and bituminous coal. During the last two months anthracite culm, which contained only 3 per cent. or 4 per cent. of volatile constituents, had been most successfully used under stationary boilers in America. Anthracite culms were washings at the anthracite mines, and up to now had been tipped back into the mines. They were about the lowest grade of fuel that could possibly be used. He could give particulars of boiler tests that had been made with straight anthracite culm, not even requiring the addition of bituminous coal. In the Report he had referred to the various American systems which he had investigated, the various works he had visited, and several pages were devoted to results obtained on actual installations of furnaces for different processes.

Mr. **Carrington** asked what was the quality of the puddled iron produced.

Mr. **Harvey** said he could not speak about the quality of iron made, but Messrs. A. M. Beyers & Co., who rightly claimed to be the makers of the highest grade of iron piping in America, melted and reheated their iron in powdered-coal fired funaces and were satisfied with the results. They even used it for welding their wrought iron pipe skelp. That would indicate that there was no difficulty experienced from ash deposited on the billets, blooms, or skelp that had to be rolled or even welded.

Mr. **Carrington** said it was well known that the quality of material necessary for iron piping was altogether inferior to that which was required for the ordinary iron bar in general use.

CORRESPONDENCE.

B. **Yaneske** (Sheffield) wrote that the use of powdered coal as the source of heat for reheating, annealing, puddling, or malleable iron furnaces was certainly economical if the ash deposit could be successfully dealt with, for in addition to effecting a saving in the amount of fuel required, metal loss or scaling in reheating furnaces was considerably reduced, and the burning out of carbon and silicon in malleable iron furnaces was almost avoided owing to the small amount of excess air used for combustion.

When the application of powdered coal to the acid open-hearth furnace was considered, however, it seemed to him that less oxidation of the elements to be removed from the charge would be effected by the flame during both melting and oreing periods than with producer-gas. As the removal of carbon by gas oxidation amounted to about 50 per cent. in ordinary practice using producer-gas, a considerably longer time would therefore be taken in working the charge if powdered coal were used, and much more iron ore would be required.

The carbon in the ash which would come in contact with the slag would also cause the gradual reduction of FeO from the slag, and the removal of FeO would be accelerated by the action of CaO if the fuel was high in limey ash. In that way a very thick siliceous slag would result and the process be further retarded.

If that were borne out in practice the saving in fuel by the use of powdered coal would be more than counterbalanced by the lengthening of the process, and it would perhaps be advisable under those circumstances to work with a much higher percentage of scrap with a powdered coal flame than in ordinary practice.

The control of the flame by a nozzle with swivel joints was certainly beneficial, as there was less likelihood of the flame being diverted on to the roof or side walls of the furnace as there was owing to the wear of gas ports.

There was much difficulty in procuring coals with consistently low sulphur and ash contents together with high volatile content, and it was very doubtful whether the checkers would last anything like as long as with producer-gas on account of ash deposit, even with removable ash bogies arranged below the down-take flues.

There was no doubt that the use of powdered coal would be more successful when applied to a furnace of the non-reversing type where regenerators were dispensed with (as Fig. 22, p. 52), that was, if a sufficiently high temperature could be maintained.

Mr. Harvey, in further reply to Mr. Talbot, wrote that the question of high ash content of coal as purchased under present-day conditions reacted on the successful operation of gas-producers, but could be dealt with more readily when fuel was burned in pulverised form. Low-grade fuels could be readily handled in that manner, and that might often remove difficulties now experienced on account of the increasing quantity of inert material bought as fuel. The standard of quality of high-class fuel was bound, however, in time to revert to the pre-war standard.

Perhaps tar was looked upon with most favour in America as a fuel for open-hearth steel melting, and certainly when coke-oven gas was available powdered coal would not be considered. At Gary the erection of several hundred coke-ovens meant the shutting down of the existing powdered coal plant.

In reply to Mr. Carrington, he might point out that the facilities provided for the collection of ash were described in the Report. In puddling and piling furnaces no trouble whatever was experienced by reason of fused ash settlement on the metal. Most of the liquid ash dropped off the pile before reaching the rolls, and that remaining flaked away during the first pass, and did not roll into the metal. In the puddling operation no ash would be found in the ball.

In regard to Professor Louis' remarks, freshly ground coal would, by reason of the bright unoxidised surfaces exposed, ingite more readily than "stale" coal-dust, or dust that had once been mixed with air and re-separated out. Mine-dust could, however, be burned quite readily if passed through a mill to produce uniform fineness, during which operation much new unoxidised surface would be exposed. The system suggested that small coal and dust now left in the mine, to the detriment of health and life, should be brought to the surface. Much of the fine dust prevailing in the workings would thus be removed and risk of explosion diminished. Such reclaimed dust could well be used under the power-house boilers or in the vicinity of the colliery.

To Mr. Ridge, he would point out that heat efficiency curves for ordinary methods of burning fuel on grates would show a greater falling off due to ash than curves taken on powdered-coal fired furnaces. In the latter case the particles of combined fuel and ash were so minute that the full value of the carbon and volatile constituents was obtained by instantaneous disassociation from the inert material which fell into the ash collecting chamber. In that way better value could be obtained from high ash fuels than by any other means, such as hand-firing, stoker-firing, or gas-producers. It was more than probable that coal-washing plants would return good value for capital expended in many cases, whether or not the fuel was to be used ultimately in powdered form.

In reply to Mr. Harrison, he (Mr. Harvey) did not intend to suggest that powdered coal could be applied for all heat generation purposes. There were applications quite unsuited to that system, but American engineers had clearly demonstrated the intrinsic value of powdered fuel for many uses.

He had not intended to suggest that powdered-coal firing was a new process. So far as Dr. Hatfield's remarks were concerned, a powdered-coal plant was put down at the works of the American Iron and Steel Company at Lebanon in 1903, and had been in continuous use since that year. Other instances existed of plants which had been in operation for many years, but it was only since 1913 that the several systems had been seriously developed. The extent to which the system had been applied could be gathered from reference to pp. 53–58 of the Report, whereon a record was given of plants so equipped to date. The order of importance for the successful and remunerative application of powdered coal would be somewhat as follows:

Applications Proved or about which sufficient is known to ensure Success.

Cement Burning Kilns.
Lime Burning and Analogous Processes.
Iron Ore Nodulising Kilns.
Annealing Furnaces.
Puddling Furnaces.
Copper Reverberatory Furnaces.
All classes of Steel Billet Reheating Furnaces of medium and large size.
Steam-Boiler Installations.
Waste-Heat Boiler Firing.
Piling and Bushelling Furnaces.
Heavy Forge Furnaces.
Sheet and Pair Furnaces.
Railway Locomotives.
Soaking Pits.
Galvanising and Tinning Kettles.

The application to open-hearth steel melting was only an unqualified success when furnaces could be built in accordance with latest practice.

Applications Involving some Doubt and Careful Consideration.

Light Forge Furnaces.
Bolt and Nut Furnaces.
Rivet-Heating Furnaces.
Domestic and Office Heating Boilers.

Applications requiring Further Development.

Marine Propulsion.
Internal Combustion Engines.
Application to Blast-Furnaces.

In reply to Mr. Hayes, certainly powdered coal could well be applied to any type of annealing furnace for high or low temperature annealing, with absence of temperature fluctuation, providing the furnaces were of sufficient size. Those indicated should be quite suitable.

Powdered fuel was, he might inform Mr. Fletcher, now applied to perhaps 150 puddling furnaces in America, and the practice was extending. That was the application looked upon as being the most successful. The grade of fuel would not militate against the smooth working of the furnace and would have little effect upon the product.

It was gratifying to him to learn that an engineer of such high standing as Sir William Beardmore had obtained data from America which had influenced him to the extent of trying out powdered-coal firing in his own works. The "start" was the most difficult thing to achieve despite convincing proof from numerous users.

He hoped to be able to give Mr. Savage the cost of powdered coal as against producer-gas practice in a separate technical article when he had had the opportunity of collecting reliable and up-to-date costs for the latter. In America both first cost of installation and running costs were in favour of the powdered-coal plant for certain duties. Present-day prices for machinery and steel work might perhaps reverse that situation in England.

The written information read by Mr. Christmas was generally correct, in so far as his remarks applied to open-hearth work and to furnaces fitted with close built regenerators, but quite sufficient heating surface was exposed in regenerators of the open cell, baffle, or pillar description (*vide* the successful open-hearth plant worked by the National Malleable Company at Melrose Park, near Chicago).

An equivalent degree of regeneration was not possible by that means, but sufficient preheating of the air supply for use with powdered coal could undoubtedly be effected in that manner. He could not grasp the meaning of Mr. Christmas' remarks regarding fuel introduction into the furnace or ash disposal, but he would be pleased to give any information required on that subject by letter. Less than 2 per cent. of the ash content of the coal would be emitted at the top of the stack, and in such a degree of fineness that it would represent no greater nuisance than soot deposit in the neighbourhood.

He agreed with Mr. Hutchinson in regard to powdered coal for steel-melting furnaces, but as would be inferred from data contained in the paper and the discussion thereon there was still room for effecting economies in many directions by using coals in powdered form.

The relative essential merits of gas-producers and powdered-coal plants had been reviewed by Mr. Harbord, and it was a question for the works engineer to weigh up the capital cost of either system in relation to the fuels that could be purchased locally and handled by either method. Feed screw apparatus was rarely worked up to its maximum limit for the reasons explained by Mr. Harbord, and an ample margin was always allowed in order to prevent "packing." All advocates of powdered coal for open-hearth steel melting agreed that the best results could only be obtained when the best class of fuel was purchased; certainly a limit of 6 or 8 per cent. ash content was advisable.

In the first paragraph of Mr. Yaneske's remarks the chief advantages of powdered-coal firing were clearly stated. In America applications had generally been made on basic steel furnaces for, on account of the effect of fused ash on acid steel, that method of heating had been found more or less impractical. So long as ash and sulphur were controlled to reasonable limits, the volatile constituents of the fuel need not be high—10 to 15 per cent. V.C. would be quite sufficient to maintain the intensity of the flame when fuel was burned in the quantities required for steel melting.

THE WORK OF THE ENGINEERING DIVISION OF THE NATIONAL RESEARCH COUNCIL, WASHINGTON, U.S.A.

By HENRY M. HOWE, LL.D. (Hon. Vice-President),
Chairman of the Division.

The National Research Council of the United States is an Institution not for executing but for stimulating scientific and technical research, and to this end it aims to become an affiliation of the scientific and research interests of our country, as I will shortly explain. It derives its authoritativeness from being a Committee of the National Academy of Sciences, a body created by Governmental Charter and in general corresponding to your Royal Society. It is in effect self-directing and free from bureaucratic control.

The Council is composed of thirteen divisions, each devoting itself to a special field. I will confine my remarks chiefly to the Engineering Division as that of most interest to you, because it aims to cover all branches of metallurgy.

How do we do this work of stimulating research? Chiefly through the creation of active Committees, of which our division has now about twenty, each charged with a research believed to be of engineering importance. Each Committee is in charge of a Chairman selected for his power of leadership, as well as for his eminence. The members of each Committee are all intended to be active in executing its work, in connection with their own regular work in the laboratories or other research, educational or industrial institutions in which they are engaged. Thus we bring to bear on each problem the men fittest for studying it, and the resources of a number, and sometimes a very large number, of the best-equipped laboratories in America, such as those of the United States Bureaus of Standards and of Mines, and of other governmental bodies, of our Universities and Technical Schools, and the laboratories and works of our great industries, such as the General Electric Company, the Westinghouse

Company, the United States Steel Corporation, the Midvale Steel Company, and very many others. We do not intend to create laboratories of our own, believing that our chosen task of stimulating those in other laboratories, of helping to lessen needless duplication, and of acting as a sort of clearing-house, is best isolated from that of equipping and maintaining laboratories.

The first problem taken up by our division was the fatigue of metals, under the Chairmanship of Professor Herbert F. Moore of the University of Illinois, with six other members representing the United States Bureau of Standards, two institutions of learning, and four industrial research departments.

The thorough study of fatigue, as influenced by the microstructure, the composition, and the condition of the metal and the ranges and frequency of repetition, requires such very extensive and prolonged tests that the world seems to have balked at it. It needs an attack on a national if not indeed on an international scale.

Professor Moore is approaching his problem in a statesmanlike way which, if persevered in, should place our knowledge of fatigue on a plane much higher than its present one. He has asked me to seek the co-operation of fatigue-students here, in France, and perhaps in the Neutral States.

The Research Council has not the funds to finance twenty such investigations for each of its thirteen divisions. In this and other cases we hope to get the money needed from the presumptive beneficiaries of the research.

Three other of our Committees may here be mentioned as treating metallurgical problems of importance sufficient to interest you: those on Alloy Steels, on the Improvement of Metals by Treatment at a Blue Heat, and on the Heat Treatment of Carbon Steel, under the Chairmanship of Dr. John A. Mathews, the first Carnegie Prize Scholar and President of the Halcomb Steel Company, of Professor Zay Jeffries of the Aluminium Castings Company, and of the present author.

Much as has been written on the heat treatment of carbon steels, much more remains to be learned to enable us to use this wonderful substance to the best advantage. For all the standard compositions we ought to be able to correlate the microstructure, the tensile, fatigue, and shock properties, and the heat treatment.

I include here the various degrees and procedures in normalising, annealing, and sorbitising.

If our knowledge is defective as regards carbon steel, it is tenfold more defective as regards the many alloy steels. Here mere fashion and guesswork has played a part far from creditable to us. An anecdote may illustrate this. A certain American cannon maker was much troubled with flakes. An experienced metallurgist, acting as Colonel of Ordnance, suggested halving the nickel content. This lessened the flakes greatly, without preventing the product from passing the reception tests. He then suggested omitting all the nickel. On doing this the flakes disappeared almost totally and the product continued to pass the reception tests. Here a costly addition of 4 per cent. of nickel was a positive damage, as far as concerns the reception tests.

Since the eighties, when Stromeyer pointed out some remarkable effects of blue heat treatment, we have known vaguely that something wholly unexplained occurs in this range of temperature. In some cases the damage and in others the benefit caused by manipulation in this range has been so great that our present ignorance is a reproach.

Three of the four Committees, the work of which I have now described to you, are to deal primarily with carbon steel. In order that we may all operate on exactly the same material, and hence that our results may be strictly comparable, Dr. H. C. Boynton has induced the John A. Roebling's Sons Company, the celebrated wire-drawers, generously to make for our joint use several tons of wire billets of acid open-hearth steel, holding several additional tons in reserve for future investigations. Every precaution will be taken to reduce the quantity of inclusions to a minimum.

Our method of making ourselves an affiliation of American engineering research interests is to have our Engineering Division composed first of sixteen official representatives appointed by our most important engineering societies, and second from seven to twelve members at large chosen by these representatives. The division thus constituted elects its own Chairman. All these appointments are subject to the approval of the Executive Board of the National Research Council and confirmation by the President of the National Academy of Sciences.

In addition to carrying on this Committee work, the Council hopes to be useful in improving the general environment of research, for instance by propaganda aimed to cause our Institutions of learning to favour research by their own staff far more than at present, and to impress on the various industries the great benefits which the more progressive establishments are now gaining from their own researches.

Each of our divisions must adapt its tactics to the conditions of its own branch of science or technology. Each of us recognising the experimental nature of our work, should profit by the experience of the others. We believe the experiments well worth trying most earnestly.

Looking at the annual crop of the products of research, the annual addition to the stock of human knowledge, we recognise that it is capable of becoming one of the world's most valuable crops, worthy of planning, fertilising, harvesting, and distributing with as high a statesmanship as is applied to other products of human activity.

DISCUSSION.

Professor H. M. **Howe**, Honorary Vice-President, in opening the discussion on his paper, said objection had been raised in some quarters to the kind of committee work mentioned in the paper, on the ground that it did not tend to stimulate individual activity, but rather to repress it. If that were true he should have very serious doubts as to the wisdom of carrying on committee work, but he believed that experience in the past had shown what might have been anticipated, namely that if those committees were wisely directed, so far from repressing individual initiative, they would have the opposite effect. The experience of the International Astronomical Society had shown that very clearly. Contact with the stimulating leadership of men of very great eminence, instead of tending to discourage men, tended to encourage them, and to lift them to a higher plane. A second reply to the objection, if it were a valid objection (which he did not think it was), would be that it applied chiefly to the individual and not to the community. The individual was a very important factor of the community, but the community should come first, as the benefit of the community was the end to be striven for, and the benefit of individuals was only a means towards that end. If, therefore, the system of committee work referred to increased the product of research, yet did not stimulate, but repressed, individual initiative that would hardly be a conclusive objection.

Dr. W. **Rosenhain**, F.R.S. (National Physical Laboratory), said it was always an advantage to hear Dr. Howe at any time on any subject on which he was willing to speak. The particular subject with which Dr. Howe had dealt was one of very great topical interest, because the whole question of the organisation of research was very much in the air, and was of very great importance to Great Britain at the present time. He thought that perhaps the most interesting parts of Dr. Howe's statement were the remarks which he had just made, and although he agreed with what Dr. Howe had said, there was one point on which he would not say he "joined issue," but with regard to which he would ask Dr. Howe's reconsideration. Dr. Howe suggested that even if it were true that organisation of research did tend to repress the initiative of the individual, that would not be so great a loss, because it was not the individual but the community which counted. He (Dr. Rosenhain) agreed so far as that final statement was concerned, but the advancement of scientific knowledge was necessarily a matter of individual initiative, and unless the individual initiative of the research worker could be stimulated and not repressed, a great deal of the work done would be comparatively unfruitful, because it would be mere systematic routine investigation. There was room and need for much of that systematic routine investigation. Many of the questions which the committees referred to in the paper were dealing with needed that kind of work, and he hoped would receive it in increasing measure, both in America and in Great Britain. There was, however, a good deal of pioneer work to be done, and the men capable of doing that work needed every encouragement and every stimulus, although he was far from suggesting that it was for their benefit at the expense of the benefit of the community. It was the other way round. If those men were stimulated, and in measure as they were stimulated, the community would benefit by their exceptional work. He did not, however, think the danger was real, because those in Great Britain had had a good deal of experience of committee work during the last four or five years, both in connection with research and other matters, and so far from the organisation of those committees serving to hinder the initiative of the individual, it frequently, he thought, served as a stimulus. It brought the individual into frequent contact with other men working on similar subjects, and there was that element of human rivalry which was inevitable in such cases, and acted as a very valuable and important stimulus. Again, it could not fail to be recognised that there were those large questions which could only be investigated and studied by the systematic collaboration and co-operation of the industry and of research workers with large resources at their disposal, and probably such organisations as the author had described in America and a somewhat similar organisation, though not on so large a scale, as was contemplated in Great Britain, were much the best that could be got together for such a purpose. He thought he was right in saying that all persons not only welcomed and applauded the work which was being done in America in the matter, but would render every possible assistance.

Professor T. **Turner** (Birmingham University) said the members were much indebted to Dr. Howe for having brought such an important subject before them. The organisation of research in America had already proceeded farther than it had done in Great Britain. The Department of Research of the United Kingdom had, however, formed a number of committees, and was proceeding on lines resembling those outlined by Dr. Howe. In the first place it was, he believed, a very wise course which had been adopted in America, that the central organisation should not endeavour itself to conduct researches, but should arrange for others to do so, stimulate their work and provide them with means, and should also draw into the net as many of the large laboratories and works as could be persuaded to assist. On those lines progress could be made. Great Britain had already derived much benefit from researches conducted in America, particularly those published by the Bureau of Standards and similar bodies. The general scheme outlined in the paper showed a broad and wise outlook, and was likely to yield important results.

Dr. F. G. COTTRELL said he had had the pleasure of being associated with some of the committees of Dr. Howe's Division of the Research Council in America, which had in particular reacted upon the Government Service, especially in connection with mining. He (Dr. Cottrell) was a member of the United States Bureau of Mines, and the Research Council formed a particularly useful connecting-link between the permanent official bodies of the Government's own service and the academic interests throughout the States—the Universities and technical schools on the one side, and the large research establishments of the industry on the other. There was always need for co-ordination between those agencies. There was a tendency for each to become so intent on the particular programme they were carrying out, that the work of liaison was to some extent neglected. A body devoting itself specifically and solely to such co-ordination could do a great deal of good, and was often in a position to initiate work which it would be impossible for one of the individual agencies themselves to initiate. That had been very much in evidence during his war work. During the past two months while he had been in France, the same problems had arisen. The National Research Council at Washington had cabled him to represent them at the meeting of the International Chemical Council which had had its first meeting in Paris about a month ago. That organisation had been indebted for its creation and initiation to Professor Henry Louis, President of the British Society of Chemical Industry, and Mr. Kessner, the President of the French Society of Chemical Industry. Out of their efforts grew the Council, and the success with which that meeting had been attended, in bringing together the technical and the academic interests in the whole of the chemical field, had been exceedingly marked. The French had joined very heartily in the movement, and were highly appreciative of the possibilities of such an international co-operation. Parallel with that, however, was the larger movement, namely the association of various organisations similar to what they had had in the States in the International Research Council, and the association of those into a larger international body or committee which could further international co-operation. The Italians had recently formed their group, and the work of creating a similar group in France was well advanced. A Bill had passed the Chamber of Deputies, and was going to the Senate, which provided for converting the section of the French War Ministry which dealt with inventions and scientific novelties into a peace-time body along those general lines, and the attempt was being made to couple that directly with the academic interests through the Academie, or some other purely scientific bodies, similar to the work which was being done in Great Britain through the Royal Society and other organisations, and which America had tried to start through the National Research Council. Both the technical and pure science interests were uniting most heartily, and it was in fact largely in connection with that matter that he had come over to England to meet Dr. Howe, who brought the latest connections from America. Dr. Howe would find, when he reached Paris, that the movement was flourishing, and that he had a fine piece of work to take up.

Professor H. LOUIS, Member of Council, emphasised very strongly the point mainly in his mind at the moment, namely the international side of the question. Hitherto work had been carried out too much in water-tight compartments, and Dr. Howe's admirable paper was in some respects an evidence of it. There were very strong reasons why forces should be combined. He had never, like a good many other people, made a fetish of research with a capital R, or looked upon it as the one great thing to aim at, and he had never been anxious to put everybody on to research work, because his own view was that the man capable of doing real research work was not born every day. It was not every day that a Bessemer, or a Ramsay, or a Crookes was born. Committees such as were being appointed in America and in Great Britain would do admirable service on the lines Dr. Rosenhain had pointed out, not by carrying out research, but by forming a body of men capable, he hoped, of sufficient discrimination to pick out those who were capable of carrying out research which would really advance the science of technology. Such men were rare, but they could be found, and he did not see how any machinery other than that provided by such committees could find them. It was surely right that such men, in whatever country they were born, should be looked upon not as national, but as international assets for the advancement of technology and science of the entire world. It was only by international co-operation between those research committees that anything of the kind could be done. International co-operation could get through a great deal of useful, he might say indispensable, spade-work which had got to be done to clear the ground for such important researches as he had in mind. Dr. Howe had stated that one of the American steelworks had been good enough to make for them a number of ingots of steel for experimental purposes, and he presumed that they would begin by analysing them. A sub-committee of the Iron and Steel Institute had been doing precisely the same thing in Great Britain with Dr. Stead as Chairman. The first step taken had been to obtain a number of ingots made of steel of approximately definite composition and to get them analysed, so that a beginning might be made by providing uniform standards of composition. To his (Professor Louis') mind the very first thing which the American National Research Council or the committee dealing with that branch of investigation ought to do was to exchange samples with the British body. The same applied to France, to Italy, and other countries. At any rate, the first step should be settled, so that when reference was made to a steel containing say 0·1 per cent. of carbon, everybody should know that they were talking about the same thing. At the present time each worker had his own methods of analysis. British analysts were trying to get standard methods of analyses for steel. He wanted to go further: he wanted an international standard and to get all the workers in the different countries interested in iron and steel to exchange specimens and co-ordinate their methods. The International Research Federation, or whatever it was called, should form a central body with which all the different research committees of the different countries could co-operate. Then, he felt, something really useful would have been inaugurated.

Professor H. M. Howe, in reply, said he was glad that Dr. Cottrell and Professor Louis had emphasised the international aspect of the matter. He had only been speaking of the part which America had been trying to take in that movement, but it was as an international movement that it was going to have its great value. His reference to the steel was rather to indicate the interest which had been taken in the matter by manufacturers in America. One of America's very best makers of high quality steel had made voluntarily a very great quantity of steel at his own cost for the purpose. It was encouraging that the industries recognised the work. The various committees were operating on identical material, and he hoped there would be enough left to interchange with Great Britain.

MODERN STEEL METALLURGY.

(CALCULATION AND COMPARISON OF PROCESSES.)

By CHAS. H. F. BAGLEY (Stockton-on-Tees).

The object of this paper is to present a simple and reliable method of calculating the consumption of materials and the technical results in the manufacture of steel from any kind of pig iron by any standard process, so that their relative advantages can be estimated and compared with some degree of confidence, instead of remaining simply matters of opinion and experiment. In the "heavy" steel trades the final cost of the ingots must always be the leading factor, and the best method of producing them cheaply in any district should be a matter of no uncertainty. The system described is essentially synthetic rather than analytical, involving various assumptions in lieu of precise data; but its substantial accuracy is confirmed by the general agreement between the calculated figures and the actual results by all the standard processes. The author worked out this system some years ago for his own use—particularly in connection with the basic open-hearth process—and has constantly employed it since with good results.

Slag Formation and Character.—In any refining process involving molten materials a slag is formed consisting essentially of the products of the elements removed (other than gases) in combination with suitable fluxing material (either derived from the metal itself or intentionally added)—together with a proportion of the active reagents employed, for which this slag is the vehicle. These constituents must be present in such proportions that they are mutually self-fluxing and self-satisfying at the prevailing temperature; so that the slag is reasonably fluid and inactive on the hearth of the furnace. At the end of the process it should carry but little excess of the active reagents—so that its action on the metal has almost ceased—and should have a physical consistency and condition that will allow it to be easily separated and removed. The final temperature is governed by the physical requirements of the metal—which are fairly definite and constant; and the composition of the slag, being merely an incidental product, must be regulated to suit so that its condition is right at tapping temperature of the metal. In the molten state, such a slag may be considered as essentially a complex solution of acids and bases rather than a definite chemical compound; their proportions being determined by the temperature, and the valency of the constituents as acids or bases, rather than by definite chemical formulæ—regardless of whatever definite compounds may be crystallised out later. In steel melting no great range of finishing temperatures is permissible, and the physical conditions of both metal and slag are fixed within comparatively narrow limits, within which the slag may be neither too thick nor too thin, and its composition is, therefore, fixed within a similar narrow margin, if its condition is to be satisfactory. It has always been the custom of practical men to judge of the progress of operations, and the quality of the metal, by its fracture and by the appearance of the slag, a method which, though apparently primitive, is thoroughly sound and practical, affording to the experienced man a visual indication of the actual physical conditions obtaining. It is almost an axiom in practice that if the slag be right, the metal also will be right.

Acids and Bases.—In a steel slag, the chief constituents—none of them individually very fusible—may be grouped into two main classes—Acids and Bases—which mutually flux and neutralise each other at quite moderate temperatures when present in approximately equal proportions. At higher temperatures a slag often becomes too thin and active and attacks the fettling material of the hearth; the proportions must then be altered to raise its melting point and reduce its fusibility correspondingly. An excess either of acids or bases is required, according to the nature of the hearth material, beyond the proportions required for fusibility at moderate temperature—as, for instance, for a mixer slag—and if not already present must be supplied by suitable additions, failing which, the slag will help itself from the hearth materials until it is "satisfied" or approximately neutralised at that temperature. The schedule of steelworks slags given later illustrates the point very clearly, and is worth careful attention. The figures quoted are for final or tapping slags only, and are taken from actual practice at many different works in England, Germany, and America, operating on various irons, by various processes, under very varied conditions. They may be taken as fair averages for good practice, whatever the pig iron. For calculating purposes, the composition of the slag as run to waste—usually the tapping slag—is the only possible basis, regardless of what it may previously have been. During the slag formation period and at early stages of the process, it is in a state of constant chemical activity and change until its active reagents, FeO and Fe_2O_3, approach exhaustion. Its composition will vary considerably, therefore, according to the extent and nature of the additions made, the progress of the reactions, and the temperature conditions of the moment. Slags from continuous processes—such as refining mixers, in which there is no finality—are always irregular, and many vary within wide limits for the same reasons. The final slag as run to waste is thus the only sound basis for calculations; and whether run off on tapping or before, it should carry a minimum of free oxides, together with the maximum of acids permitted by the temperature at that period.

As regards the various constituents, it may be noted that they are nearly all oxides—usually the lowest oxide the element is capable of forming; and some of them, notably those derived in part from the metal, are therefore capable of being partially reduced in the later stages by the remaining carbon of the bath, especially in the absence of sufficient free oxide of iron. Not only has the slag an oxidising effect on the metal, but the metal and its metalloids have an equal reducing effect on the more active constituents of the slag. A general principle is that any element which is reducible in the blast-furnace is oxidisable in the steel furnace or converter and removable as an oxide in a suitable slag containing some constituent with which it can enter into combination—failing which it will be again reduced by the remaining carbon of the bath, unless an excess of some more reducible oxide—say Fe_2O_3, FeO—is present, when it may be partly removed as an oxide in the slag. The iron oxides may be used to limit the extent of its reduction, but will not alone entirely prevent it. In any case, the reducing influence is always present, and tends to prevent the entire elimination of any element, at least until the carbon is gone, and traces of them all are usually found in the finished steel. In the acid process 0·02 to 0·04 per cent. of silicon and 0·03 to 0·06 per cent. of manganese are usually found, either never oxidised or subsequently reduced; and, in the basic process, traces only of silicon and 0·10 to 0·40 per cent. of manganese are found. The difference arises from the fact that MnO has a great affinity for SiO_2, which is present in excess in the acid slag, and little MnO is therefore reduced. In a basic slag, however, there is no excess of SiO_2, and the MnO is more liable to the reducing influence of the carbon. Quantitatively these traces are almost negligible and have no material effect on the calculations, but they affect the general quality or condition of the steel considerably and account largely for the characteristic differences between steels made by various processes.

STEELWORKS SLAGS.

It may be objected that the average acid contents here shown are on the high side in some cases—especially for basic slags from fixed open-hearth furnaces—and set a standard not always reached in practice. This may possibly be so, the result being to show these processes rather too favourably, but for the sake of comparison between basic open-hearth processes, the slags are all placed on the same level. It also seems useless to compare poor practices together, and where actual results fall short of these figures—which often are realised—there appears to be room for improvement. It is frequently observed that one charge takes considerably more lime than another, though using the same quality and quantity of iron, especially if worked slowly or delayed for any reason, constant fresh additions being needed to keep the slag in proper condition and prevent it from getting thin. In these cases, the total acids are invariably low—possibly down to 18 per cent. or less—and the CaO higher than here shown—possibly up to 58 per cent.—under which conditions the lime consumption may be as much as 75 per cent. above normal. The subject will be more fully dealt with later when considering the removal of sulphur and the production of phosphate slags.

Normal Steelworks Slags.

Process .	Acid Bessemer.		Acid Open-Hearth.		Acid Open-Hearth.		Acid Mixer.		Basic Mixer.		Basic Open-Hearth.		Basic Open-Hearth.		Basic Open-Hearth.		Basic Bessemer.	
Pig Iron .	Hæmatite.		Hæmatite.		Hæmatite.		Any Iron.		Any Iron.		Hæmatite.		Common Forge.		"Thomas."		"Thomas."	
Additions .	Nil.		Oxides, Lime.		Oxides only.		Oxides, Lime.		Oxides, Lime.		Oxides, Lime.		Oxides, Lime.		Oxides, Lime.		Lime.	
Normal variations.	Range.	Mean.	Range.	Mean.	Range.	Mean.	Range.	Mean.	Range.	Mean.	Range.	Mean.	Range.	Mean.	Range.	Mean.	Range.	Mean.
SiO_2 . .	62/68 =	65·0	57/63 =	60·0	48/52 =	50·0	38/46 =	42·0	36/42 =	39·0	25/29 =	27·0	14/22 =	18·0	10/14 =	12·0	6·0/10·0 =	8·0
P_2O_5 . .	...	...	...	...	...	...	...	...	0·5/1·5 =	1·0	0/2·0 =	1·0	7·0/13 =	10·0	14/18 =	16·0	18·0/22 =	20·0
Al_2O_3. .									0·5/1·5 =	1·0	1·0/3·0 =	2·0	1·0/3·0 =	2·0	1·0/3·0 =	2·0	...	...
CaO . .	4·0/6·0 =	5·0	12/18 =	15·0	5·0/9·0 =	7·0	9·0/15·0 =	12·0	40/48 =	44·0	46/50 =	48·0	46/50 =	48·0	46/50 =	48·0	48/52 =	50·0
MgO . .									5·0/7·0 =	6·0	4·0/6·0 =	5·0	4·0/6·0 =	5·0	4·0/6·0 =	5·0	4·0/6·0 =	5·0
MnO . .	8·0/12·0 =	10·0	5·0/15·0 =	10·0	5·0/15·0 =	10·0	4·0/8·0 =	6·0	4·0/6·0 =	5·0	4·0/12·0 =	8·0	4·0/12·0 =	8·0	4·0/12·0 =	8·0	4·0/12·0 =	8·0
FeO . .	18/22 =	20·0	12/18 =	15·0	28/38 =	33·0	35/45 =	40·0	3·0/5·0 =	4·0	5·0/14·0 =	9·0	5·0/14·0 =	9·0	5·0/14·0 =	9·0	5·0/14·0 =	9·0
Totals .		100·0		100·0		100·0		100·0		100·0		100·0		100·0		100·0		100·0
Total acids	65·0	= 1·86/1·00	60·0	= 1·50/1·00	50·0	= 1·00/1·00	42·0	= 0·725/1·00	40·0	= 0·666/1·00	30·0	= 0·43/1·00	30·0	= 0·43/1·00	30·0	= 0·43/1·00	28·0	= 0·39/1·00
Total bases	35·0		40·0		50·0		58·0		60·0		70·0		70·0		70·0		72·0	
Approximate finishing temperatures °C.	1500/1600		1400/1500		1400/1500		1200/1300		1200/1300		1400/1500		1400/1500		1400/1500		1500/1600	

METHOD OF CALCULATION.

By whatever process effected, the essential operations of steel melting are:

1. The oxidation of the impurities of the raw pig iron.
2. The safe removal of the products—as slag.
3. The maintenance of a temperature high enough to keep the metal molten and allow it to be cast into moulds.
4. The formation, or provision, of a slag of proper physical consistency—fluid and appproximately neutral to the lining of the hearth at the finishing temperature of the process—and finally almost exhausted of active reagents.

Oxidation Table.—For a quantitative account of the process and results, the weight of the metalloids to be oxidised may first be considered. From the average composition of charge, it is a simple matter to calculate the weight of oxygen required and of the products formed. Whatever the source of this oxygen, these quantities are fixed and definite and in simple chemical proportions. Thus, the oxidation of:

1 unit of	carbon	requires	16 ÷ 12 = 1·33	of oxygen,	forming	2·33 of	CO gas
,,	silicon	,,	32 ÷ 28 = 1·14	,,	,,	2·14 ,,	SiO_2
,,	phosphorus	,,	80 ÷ 62 = 1·29	,,	,,	2·29 ,,	P_2O_5
,,	manganese	,,	16 ÷ 55 = 0·29	,,	,,	1·29 ,,	MnO

Units.—The units employed may be anything from molecules to tons, but throughout these calculations ton units are employed; and 100-ton charges are considered, so that each 1·00 per cent. by analysis represents 1·00 ton, and the decimal system is thus retained throughout, with its customary advantages. Calculations are accurate to the 3rd figure, and approximate where given to the 4th—ordinary slide-rule limits.

Oxides.—The oxygen required can be calculated to its equivalent in air, or, subject to certain reservations, in pure Fe_2O_3, or its equivalent in ore of given analysis; and the weight of the metallic Fe, &c., introduced therewith is easily found. The other items, SiO_2, P_2O_5, Al_2O_3, CaO, MgO, MnO, &c., also introduced, may often be important, especially SiO_2, as compared with the amounts derived from the metal itself, and should be taken into account in calculating the slag make and analysis, lime consumption, metallic losses, yield, &c. The consumption of oxides thus ascertained should be the maximum in good practice, and should rarely be actually reached, as a proportion of the metalloids will always be oxidised by the flame in an open-hearth furnace. Nevertheless, it is often exceeded, especially in hot metal processes—notably in Monell practice—with excessive slag production and needless waste of oxides and lime in the form of half-spent slag. The actual oxide requirements for a given charge or furnace are thus somewhat variable, but for the sake of uniformity they are taken throughout at the full calculated values—which point should not be overlooked when the subject of metallic yield and losses comes to be considered.

When cold pig iron and scrap are to be used, allowance must be made for the inevitable metallic loss incurred in melting down; and the oxide formed—as Fe_3O_4—should be deducted from the requirements of the charge. It should be noted that there is usually a small percentage of Fe_2O_3 as well as of FeO to be found in the slag—even towards the end—indicating that although FeO may be in process of reduction by the carbon of the bath, it is simultaneously being oxidised to Fe_2O_3 by the flame to a small extent. This catalytic action partly explains the fact that some charges do not actually use nearly so much oxides as their calculated requirements—which is found to be the case especially with a slow furnace or a dull heat. On the other hand, a keen furnace will take almost its full calculated quantity—indicating that the oxide is quickly reduced and so is not exposed in sufficient quantity nor long enough to the oxidising action of the flame to allow this catalytic action to occur to any great extent.

Products.—The products of oxidation, other than CO and CO_2 which escape as gases, will all pass into the slag, besides the impurities introduced from outside sources—lime, oxides, sand on pig iron, wear of furnace hearth and linings, &c. For the sake of uniformity, this last item is omitted throughout on account of its irregularity and uncertainty, though it is by no means always negligible. The other factors are taken as constant throughout, at the following values:

Cold pig iron—sand allowance at ¼ cwt. per ton = 1·25 per cent. SiO_2.
Kirunavaara ore (C) at 65·0 per cent. Fe and 3·0 per cent. SiO_2.
Burnt lime (C) at 96·0 per cent. CaO and 2·0 per cent. SiO.

Slag Make.—In a normal tapping slag of proper temperature and consistency there is no great range of variation in composition, and the total weight of acids present will therefore determine approximately the average make of slag. Thus, if the total SiO_2 produced from 100 tons of iron by an acid Bessemer converter be 6·30 tons, and the final slag normally contains 63·0 per cent. SiO_2, the average make of slag will be $6{\cdot}30 \div 0{\cdot}63 = 10$ tons per 100 tons of iron. So also in the basic process, if the total acids SiO_2, P_2O_5 from 100 tons of iron *plus* that introduced by the necessary lime and oxides amount to 5·60 tons, and the final slag normally contains 28 per cent. of acids (SiO_2 and P_2O_5), the average make of slag will be $5{\cdot}60 \div 0{\cdot}28 = 20{\cdot}0$ tons. In preliminary refining or mixer furnaces, taking into consideration the acids produced and the normal acid contents of the slag made (as controlled by the working temperature), the same applies. At particular works the final slags may vary in acid contents from the figures shown in the schedule of steelworks tapping slags here given, and the basis of calculation will require amending accordingly, but the principle still holds good and the average results will be reliable.

Lime.—The burnt lime required is at once found from the average make of slag as above, taking into consideration the CaO contents of the lime, which rarely exceeds 96 per cent. Thus, for an acid slag to contain 9·6 per cent. CaO, the burnt lime needed will be $9{\cdot}6 \div 96 = 10$ per cent. of the slag made; and for a basic slag, to contain 48 per cent. CaO, the burnt lime required will be $48 \div 96 = \frac{1}{2}$ of the total slag made. No account is taken here of any CaO introduced by ores or taken up from the hearth or fettling materials. It does not affect the CaO requirements, but should be deducted from the quantity to be supplied if present in appreciable quantity.

Slag Analysis.—Having ascertained the total make of slag, the SiO_2, P_2O_5, and MnO contents can now be stated in percentages, and its value as a fertiliser or otherwise determined.

The CaO contents have already been decided, and percentage allowances can usually be made for the inevitable Al_2O_3 and MgO within normal limits as per schedule; though under exceptional circumstances these items may need to be specially estimated. There remain only the iron oxides, FeO and Fe_2O_3, which, as a rule, may be taken by difference and will not be far off the mark. They may be considered together as FeO, and together with MnO constitute the bases in an acid slag; but in a basic slag they may be regarded simply as diluting the primary acids (SiO_2, P_2O_5) and bases (CaO and MgO) of the solution. Campbell, Harbord, and other authorities agree that FeO and MnO are together approximately a constant proportion in the slag, but as MnO is more liable to volatilisation than FeO, it may, therefore, be less than as calculated—its place being taken by FeO. Hence, if there be much MnO present, the FeO contents will be relatively low, and *vice versa*, MnO displacing FeO within this proportion; but when for any reason the two are present in excess, it is at the expense of the chief constituents, and the slag calculation should be made again on an amended basis of acid and CaO contents accordingly. Similarly when the two together are less than normal, the slag will be found to contain higher percentages of acids and CaO than those on which these calculations are based. In this connection it should be remembered that if FeO is present in excess the carbon may be gone before tapping heat is reached, and the steel will be wild; while if deficient, the reactions will fall off and the carbon may "stick" until further ore additions are made—conditions which it is the steel-melter's business to avoid.

Metallic Yield.—An approximate metallic balance-sheet may now be drawn up, though some of the losses are more or less indeterminate and have to be assumed from known results in actual practice. On one side may be debited the metallic charge, Fe received from the oxides, and the ferro-alloys used in the ladle; and on the other the furnace may be credited with the metalloids oxidised, Fe carried off as oxide in the slag, sand allowance, metallic shot in the slag, scrap lost in the slag ladle, pit scrap, metal scrap, charging and teeming splash and spillage, metal volatilised, &c. A typical balance-sheet is as under:

Dr. Metallic charge	100·00	*Cr.* Sand allowance	nil
Fe from ores	16·30	Metalloids oxidised . . .	6·20
Ferro alloys (say)	0·70	Fe as oxide—in slag . .	1·76
		Mechanical losses, volatilised and unaccounted for } estimated .	4·00
		Balance—ingots and scrap .	105·04
Total . . .	117·00	Total . . .	117·00

To keep a reasonably accurate account over a period, a steelworks should in every department be kept as clean and free from scrap of all sorts as possible. Everything must be weighed in and out and complete analyses frequently taken and duly averaged together. Even then an exact account will always remain an impossibility. Such a balance-sheet can only be approximate; but it is none the less interesting and useful for making comparisons or for setting up a standard of efficiency. It indicates the various directions in which losses may occur and their relative importance. Particular attention should be paid to the mechanical losses—especially in the handling and transfer of molten steel or metal, and to all apparatus and machinery employed, with a view to minimising the more or less inevitable waste and carelessness in this direction. It is most important that molten metal be handled as rarely and expeditiously as possible. There is usually far too much scrap and waste, metal skull, spillage, and pit scrap, &c., to be seen about a steel plant, all representing losses of yield—some recoverable, others final. The importance of these losses should be better appreciated, and the fact realised that with ingots at, say, 75s. per ton in normal times, each unit gained or lost represents a value of approximately 9d. per ton.

As regards metallic shot and scrap lost in the slag where basic phosphate slag is made and ground for fertilisers, the bulk of it can be recovered, and the loss in this direction approximately ascertained. Otherwise, it can only be guessed at from a look over the tip; but even where facilities and supervision are good it is rarely less than 4 per cent. of the slag made, or say 1·00 per cent. of the metallic charge, and may be very much higher. A serious fault of the tilting furnace is the impossibility of running the slag off entirely without losing metal into the slag tub; for whenever the furnace is tilted the metal, being very much heavier than slag, finds its level and comes up first, whereas the slag remains lying on a perfectly level surface. Some loss of metals (Fe and Mn) by volatilisation is inevitable, but it may be excessive—probably through too thin a covering of slag on the bath, or due to a needlessly high temperature. It is seen—oxidised—in the dense brown fume of the converter, and in the lighter brown smoke from the open-hearth furnace chimney; and is often found oxidised and condensed in the ports, flues, and checkers as a very light oxide—Fe_2O_3—exactly like purple ore in appearance (though not in weight), though purple ore may never have been used at all in that furnace. It is constantly found in the checkers of basic furnaces working the Martin process without a pound of ore being used.

The full calculated quantities of Fe introduced by the oxides may not actually be used in practice, as already noted, and the yield and balance-sheet will be affected accordingly. Provided that they are efficiently used, and not wasted, the higher the consumption the better from this point of view; for the Fe unit in the form of steel ingots is normally worth 9d., as against its cost in the form of ore at say 4d. in normal times—a difference of 5d. per ton of ingots.

Whatever the process, there will inevitably be such mechanical losses, some recoverable (though as scrap only) and others final; besides which some margin must be allowed for discrepancies and approximations within probable limits of accuracy. In order to compare results, it is necessary to adopt a reasonable figure as a standard for these "unaccountable" losses by each process; and from various data, checked by working back from known yields of various processes, the author arrives at the following figures, which are adopted throughout these calculations:

"*Mechanical Losses,*" "*Volatilised,*" *and* "*Unaccounted.*"

			Per Cent.
1.	By the acid Bessemer (direct metal) process		6·00
2.	,, basic Bessemer (direct metal) process		6·00
3.	,, basic open-hearth (direct metal) process		4·00
4.	,, basic open-hearth (cold pig iron and scrap)		3·00
5.	,, acid open-hearth (cold pig iron and scrap)		2·00
6.	In the acid Bessemer preliminary process	4·00	plus 4·00 further loss in the basic open-hearth finishing furnace.
7.	,, basic Bessemer preliminary process	4·00	
8.	,, basic open-hearth (mixer) preliminary process	2·00	

N.B.—All these losses are per ton of the *charged weight*—not per ton of product, to give which they must be divided by the yield realised.

SULPHUR IN THE BASIC PROCESS.

The elimination of sulphur in the basic process is a fairly simple matter, and a much higher limit of sulphur in the pig iron is therefore permissible than in the acid process. It will usually fall to something less than 0·10 per cent. at a low temperature in the mixer or in melting, without assistance, provided the metal contains sufficient manganese ; and it falls further, as the process proceeds, down to 0·08 per cent. or 0·06 per cent. Such difficulty as occurs is not in reducing it to this level, but in removing the next few points, when required ; yet the ancient prejudice that basic steel requires to be lower in sulphur than acid steel in order to be equally good still lingers—this notion apparently arising from the fact that basic steel usually is lower, and is in that respect a better material. When especially low sulphur steels are required—under 0·05 per cent. sulphur—they can be made without much difficulty other than reduced output—which must be accepted. The conditions for its removal in the furnace are : (1) a more basic slag, and (2) a higher temperature, or, in the language of the furnacemen, " a thick slag and a strong boil." Sulphur is slow to move (but does not " go back " like phosphorus), and the slag should be rather " thick " from the beginning in order to ensure its removal by the time the carbon reaches the desired point. The tendency of both these conditions is to reduce the percentage of acids in the finishing slag, or, in other words, to increase the make of slag at the expense of output of steel. Its CaO contents may rise to 56 per cent. or more, and the total acids fall to 18 per cent. or less—indicating some 50 per cent. increase in slag make. For instance, if from 100 tons charged, the total acids amount to 5·40 tons, the make of normal slag containing, say, 27 per cent. of acids is $5{\cdot}40 \div 0{\cdot}27 = 20$ tons ; whereas the make of an abnormal slag containing only 18 per cent. total acids will be $5{\cdot}40 \div 0{\cdot}18 = 30$ tons—an increase of 50 per cent. in slag production. The lime consumption is still further increased, for instead of being one-half the slag make as usual, it becomes $56 \div 96 \times 30 = 17{\cdot}5$ tons—an increase of 75 per cent. The percentage of P_2O_5 is also reduced to two-thirds of what it should be, and the effect on output of steel and costs generally is serious. One need hardly urge the necessity of avoiding such practice without very good reasons—and extras. Unfortunately, in the blast-furnace, silicon and sulphur move in opposite directions—sulphur decreasing with higher silicons, and *vice versa*. Choice may be made and limits specified for either, but not both, and the usual practice is to compromise by aiming at 1·00 per cent. silicon with 0·10 per cent. sulphur—which leaves a working margin either way to both blast-furnaces and steelworks. Phosphorus is rarely mentioned in basic iron specifications!

It is frequently observed that when a furnace has been delayed for any reason, and the slag undesignedly has got into the above condition, the sulphur contents of the steel are unexpectedly and unusually low without any attempt to make them so.

Pig Irons.—For the purpose of calculation and comparison of the various processes, typical pig irons have been selected as under and are taken as standards throughout these calculations.

	C.	Si.	P.	Mn.	
1. Hæmatite—mixed Nos.	3·80	2·50	0·06	1·00	Natural hæmatite iron
2. Hæmatite—special .	3·20	1·00	0·06	0·80	Special hæmatite (American "Bessemer")
3. Common forge . .	3·50	1·80	1·50	0·60	Natural iron (Cleveland, Northants)
4. Common basic . .	3·20	1·00	1·25	1·20	Low silicon iron with proportion of foreign ores
5. "Thomas" special	3·20	0·50	2·25	2·20	Continental—high phosphorus and manganese

An appropriate iron has been selected for detailed calculation by each process as under, and the results, together with those of other possible irons, are tabulated for comparison;

Hot Metal Processes.

1. Bessemer acid process with direct molten iron—hæmatite (mixed Nos.)
2. " basic " " " —"Thomas."
3. Open-hearth basic " " " —common forge.

Scrap and Cold Pig Processes.

4. Open-hearth acid process with 50 per cent. scrap, 50 per cent. pig—hæmatite (mixed Nos.).
5. Open-hearth basic process with 50 per cent. scrap, 50 per cent. pig—common forge.
6. Open-hearth "Martin" process with 75 per cent. scrap, 25 per cent. pig—common basic.

Duplex Processes.

7. Acid Bessemer and basic open-hearth, with direct molten metal—common forge.
8. Basic open-hearth (mixer) and basic open-hearth, with direct molten metal—common forge.
9. Basic Bessemer and basic open-hearth, with direct molten metal—common forge.

BESSEMER ACID PROCESS, WITH MOLTEN HÆMATITE IRON (MIXED NOS.).

Oxidation Table.—If the steel when blown is to contain 0·20 per cent. carbon; silicon, trace; manganese, trace, there will be oxidised per 100 tons of metal charged:

		Tons.		Tons.		Tons.
Carbon	from 3·80 to 0·20	= 3·60	requiring oxygen	4·80,	producing	8·40 CO gas
Silicon	„ 2·50 „ ...	= 2·50	„ „	2·86	„	5·36 SiO_2
Manganese	„ 1·00 „ ...	= 1·00	„ „	0·29	„	1·29 MnO
	Totals . .	7·10	„ „	7·95	„	6·65 solids

Blast.—Taking normal air at 10° C. and 750 mm. pressure, under which conditions it will contain approximately 0·290 tons of oxygen per 1000 cubic metres, and assuming all carbon burnt to CO and no free oxygen to pass through unconsumed—there will be required not less than 10 (7·95 ÷ 0·290) = 274 cubic metres of free air per ton of iron.

Slag.—If the slag is to contain 65 per cent. acids (SiO_2), the total slag make will be 5·36 ÷ 0·65 = 8·25 tons; made up approximately as under:

		Per Cent.	
SiO_2	5·36 tons	= 65·0	
MnO	1·29 „	= 15·6	
FeO	1·60 „	= 19·4	(Fe = 1·24 tons)
Total . .	8·25 „	= 100·0	

Yield.—The Metallic Losses and Balance Sheet are approximately as under:

Dr. Metallic charge . . .	100·00	*Cr.* Metalloids oxidised . .	7·10
Ferro alloys (say) . . .	0·70	Fe (as oxide) in slag . .	1·24
		Mechanical losses Volatilised . . } (say) . .	6·00
		Yield—ingots and scrap . .	86·36
Total	100·70	Total .	100·70

N.B.—It is well known that in the early and cooler stages of the blow CO_2 is largely produced, and that it falls off later as the temperature rises—probably due to a portion of the blast passing through the metal unconsumed and burning the CO to CO_2 above the surface of the metal. Correspondingly more blast is required than as calculated for CO, as above, but it is easily supplied, and does not affect the calculations in any other way.

BESSEMER BASIC PROCESS WITH MOLTEN "THOMAS" IRON.

Oxidation Table.—If the steel when blown is to contain 0·20 per cent. carbon, 0·05 phosphorus, and 0·20 manganese, there will be oxidised per 100 tons of metal charged :

			Tons.		Tons.		Tons.	
Carbon	from 3·20	to 0·20	= 3·00	requiring oxygen	4·00,	producing	7·00	CO gas
Silicon	„ 0·50	„ ...	= 0·50	„ „	0·57	„	1·07	SiO_2
Phosphorus	„ 2·25	„ 0·05	= 2·20	„ „	2·84	„	5·04	P_2O_5
Manganese	„ 2·20	„ 0·20	= 2·00	„ „	0·58	„	2·58	MnO
	Totals .	.	7·70	„ „	7·99	„	8·69	solids

Blast.—Taking normal air, assumed dry, at 0·290 tons of oxygen per 1000 cubic metres—as before—there will be required not less than 10(7·99 ÷ 0·290) = 276 cubic metres of free air per ton of iron.

Slag.—If the slag is to contain 28 per cent. acids ($SiO_2 + P_2O_5$), the slag make will be approximately 6·11 ÷ 0·28 = 21·82 tons of slag, to make which there is required burnt lime (at 96·0 per cent. CaO in lime and 50 per cent. CaO in slag) = 11·3 tons. The composition of the slag will be approximately :

		Per Cent.	
SiO_2	1·07 tons	= 4·9	
P_2O_5	5·04 „	= 23·1	
MnO	2·58 „	= 11·8	
CaO	10·91 „	= 50·0	
MgO	0·87 „	= 4·0	
Al_2O_3	... „	= ...	
FeO	1·35 „	= 6·2	(Fe = 1·05 tons)
Totals . .	21·82 „	= 100·0	

Yield.—The Metallic Losses and Balance Sheet are approximately as under :

Dr. Metallic charge . . .	100·00	*Cr.* Metalloids oxidised . . .	7·70
Ferro alloys (say) . . .	0·70	Fe (as oxide) in slag . .	1·05
		Mechanical losses Volatilised . . } (say) . .	6·00
		Yield—ingots and scrap . .	85·95
Total . .	100·70	Total	100·70

Bessemer Process. Tabulated Results per 100 *Tons of Iron charged.*

Pig Iron Used.	Acid Process.		Basic Process.	
	Hæm. M. Nos.	Spec. Hæm.	Com. Forge.	"Thomas."
Oxygen required (tons) . .	7·95	5·31	8·54	7·90
Equivalent air per ton . .	270 M^3	183 M^3	294 M^3	276 M^3
Total products to slag . .	6·65	3·01	7·94	8·69
Total acids	5·36	2·14	7·30	6·11
Slag make at 65 per cent. SiO_2 .	8·25	3·30	...	...
,, ,, ,, 28 per cent. acids .	...	...	26·0	21·8
Burnt lime (for 50 per cent. CaO)	...	...	13·5	11·3
Slag Analysis: SiO_2	5·36 = 65·0	2·14 = 65·0	3·86 = 14·8	1·07 = 4·9
P_2O_5	...	...	3·44 = 13·2	5·04 = 23·1
MnO	1·29 = 15·6	0·87 = 26·4	0·64 = 2·5	2·58 = 11·8
CaO	...	...	at 50·0	at 50·0
MgO	...	...	,, 4·0	,, 4·0
Al_2O_3. . . .	...	...	...	...
FeO	1·60 = 19·4	0·29 = 8·6	4·03 = 15·5	1·35 = 6·2
Totals . . .	8·25 = 100·0	3·30 = 100·0	26·00 = 100·0	21·82 = 100·0
Metallic Balance Sheet:				
Dr. Metallic charges . . .	100·00	100·00	100·00	100·00
Ferro alloys (say) . .	0·70	0·70	0·70	0·70
Totals . . .	100·70	100·70	100·70	100·70
Cr. Metalloids oxidised . .	7·10	4·60	7·10	7·70
Fe (as oxide) in slag . .	1·24	0·22	2·92	1·05
Mechanical losses Volatilised . } (say) .	6·00	6·00	6·00	6·00
Yield—ingots and scrap .	86·36	89·88	84·68	85·95
Totals . . .	100·70	100·70	100·70	100·70

N.B.—MnO being more volatile than FeO will usually be lower than as calculated above—its place being taken by FeO, with consequent slight increase in Fe loss (as oxide) in the slag.

BASIC OPEN-HEARTH (TALBOT) PROCESS WITH DIRECT MOLTEN METAL—COMMON FORGE IRON.

Oxidation Table.—If the steel before tapping is to contain 0·20 per cent. carbon, 0·05 phosphorus, and 0·10 manganese, there will be oxidised per 100 tons of metal charged:

			Tons.		Tons.		Tons.
Carbon	from 3·50	to 0·20	= 3·30	requiring oxygen	4·40	and producing	7·70 CO gas
Silicon	,, 1·80	,, ...	= 1·80	,, ,,	2·06	,, ,,	3·86 SiO_2
Phosphorus	,, 1·55	,, 0·05	= 1·50	,, ,,	1·94	,, ,,	3·44 P_2O_5
Manganese	,, 0·60	,, 0·10	= 0·50	,, ,,	0·14	,, ,,	0·64 MnO
Totals . .			7·10	,, ,,	8·54	,, ,,	7·94 solids

Oxides.—If supplied as Fe_2O_3, this oxygen would represent $8·54 \div 0·30 = 28·5$ tons Fe_2O_3; or of ore containing 65 per cent. Fe $(70 \div 65 \times 28·5) = 30·8$ tons of ore, introducing 20·0 tons of Fe; and also SiO_2 (at 3·0 per cent.) $= 0·03 \times 30·8 = 0·92$ tons.

Slag Make, Lime, &c.—The total acids present now are:

	Tons.	
SiO_2 from the iron	3·86	= 5·08 tons SiO_2.
,, ,, ore	0·92	
,, ,, lime (say)	0·30	
P_2O_5 ,, ,, iron	3·44	
Total	8·52	

As the slag is to contain 28 per cent. acids and 48 per cent. CaO, the total slag make will be $8·52 \div 0·28 = 30·4$ tons; and the burnt lime required (at 96 per cent. CaO) will be exactly half = 15·2 tons.

Slag Analysis.—The composition of the slag will be approximately as under:

SiO_2	5·08 tons =	16·7	
P_2O_5	3·44 ,, =	11·3	
MnO	0·64 ,, =	2·2	
CaO	. at	48·0	
MgO	. ,,	5·0	
Al_2O_3, &c.	. ,,	2·0	
FeO	4·50 tons =	14·8	(= 3·50 tons Fe)
Totals . . .	30·4 ,, =	100·0	

The Metallic Balance Sheet will be approximately as under:

Dr. Metallic charge	100·00	*Cr.* Metalloids oxidised	7·10
Fe from ore	20·00	Fe (as oxide) in slag	3·50
Ferro alloys (say)	0·70	Mechanical losses Volatilised . . } (say) . .	4·00
		Yield—ingots and scrap . .	106·10
Total . . .	120·70	Total . . .	120·70

Basic Open-Hearth (Talbot) Hot Metal Process. Tabulated Results per 100 Tons of Pig Iron.

Pig Iron Used.	1. Hæm. (M. Nos.).	2. Hæm. (Spec.)	3. Com. Forge.	4. Com. Basic.	5. "Thomas."
Metalloids oxidised (tons)	7·10	4·60	7·10	6·20	7·70
Oxygen required . .	7·95	5·31	8·54	6·98	7·90
Equivalent Fe$_2$O$_3$ at 70 per cent. Fe . . .	26·2	17·6	28·5	23·3	26·7
Equivalent ore at 65 per cent. Fe . . .	28·2	19·1	30·8	25·1	28·8
Fe introduced . . .	18·3	12·3	20·0	16·3	18·7
SiO$_2$ introduced at 3 per cent. of ore . . .	0·84	0·58	0·92	0·75	0·86
Acids: SiO$_2$ from metal .	5·36	2·14	3·86	2·14	1·07
SiO$_2$,, oxides .	0·84	0·58	0·92	0·75	0·86
SiO$_2$,, lime .	0·22	0·10	0·30	0·21	0·26
P$_2$O$_5$,, metal .	...	...	3·44	2·75	5·04
Total acids .	6·42	2·82	8·52	5·85	7·23
Slag make (at 28 per cent. acids)	22·92	10·1	30·4	20·9	25·9
Lime required (for 48 per cent. CaO) . . .	11·5	5·0	15·2	10·5	13·0
Slag Analysis: SiO$_2$.	6·42 = 28·0	2·82 = 28·0	5·08 = 16·7	3·10 = 14·8	2·19 = 8·4
P$_2$O$_5$.	... ...	... ...	3·44 = 11·3	2·75 = 13·2	5·04 = 19·5
MnO .	1·29 = 5·6	0·87 = 8·6	0·64 = 2·2	1·29 = 6·2	2·58 = 10·0
CaO .	at 48·0	at 48·0	at 48·0	at 48·0	at 48·0
MgO .	,, 5·0	,, 5·0	,, 5·0	,, 5·0	,, 5·0
Al$_2$O$_3$.	,, 2·0	,, 2·0	,, 2·0	,, 2·0	,, 2·0
FeO .	2·61 = 11·4	0·85 = 8·4	4·52 = 14·8	2·26 = 10·8	1·81 = 7·0
Totals . .	22·9 = 100·0	10·1 = 100·0	30·4 = 100·0	20·9 = 100·0	25·9 = 100·0
Metallic Balance Sheet:					
Dr. Metallic charge . .	100·00	100·00	100·00	100·00	100·00
Fe from ore . .	18·30	12·30	20·00	16·30	18·70
Ferro alloys (say) .	0·70	0·70	0·70	0·70	0·70
Totals . .	119·00	113·00	120·70	117·00	119·40
Cr. Metalloids oxidised .	7·10	4·60	7·10	6·20	7·70
Fe (as oxide) in slag .	2·03	0·66	3·50	1·76	1·41
Mechanical losses } say Volatilised. . }	4·00	4·00	4·00	4·00	4·00
Yield—ingots and scrap	106·57	103·74	106·10	105·04	106·29
Totals . .	119·00	113·00	120·70	117·00	119·40

COLD PIG AND SCRAP IN HOT METAL OPEN-HEARTH BASIC PRACTICE.

A proportion of cold steel scrap—up to 50 per cent.—may sometimes be worked to advantage in direct hot metal practice, especially with a common iron, and has the effect of diluting the impurities of the iron and so reducing the consumption of lime and the make of slag in similar proportion. The oxides consumption and the metallic yield will fall in heavier proportion, owing to the large amount of metal oxidised in heating up the cold pig or scrap. To avoid chilling the molten metal all cold pig and scrap, together with most of the lime and oxides required, should be charged first and well heated before the metal is poured in. How far this heating should be carried is a matter of judgment; for if not hot enough the metal will chill—or even set—on the bottom and round the cold stock, and a long time will be spent in getting heat to "lift" it before a "clear" boil will set in. On the other hand, if overheated—say to the point of incipient fusion—and heavily oxidised, a violent reaction immediately occurs with the molten iron, and the furnace boils over; the half-spent slag, laden with excess oxide, &c., pouring out of the slag notches and doors to waste. This is the principle of the "Monell" process. Such reactions do the furnace no good, and a heavy foaming slag is usually left which takes some time to "clear." There may not then be enough of it left to do the work, and fresh additions of lime and oxides (cold) are needed to make good the loss and complete the process. Considerable loss of time and output as well as of materials results. A mean should therefore be aimed at between these limiting conditions—just short of getting such reactions—at which neither the molten metal is chilled, nor the slag lost as above, and a "clear boil" obtained in the minimum of time without loss of heat or of material. With a little experience on a given furnace, a rule can be laid down stipulating a definite time allowance (say two hours) for heating the scrap, &c., before the metal is charged.

The calculations and results are similar to those for ordinary cold pig and scrap charges of similar proportion (due allowance being made for the absence of sand), provided no slag be lost by such reactions. If a refining mixer plant is attached to the basic open-hearth steel department, it may be used within its heating capacity for melting steel scrap; and the metal will be improved for the steel furnaces in being diluted with nearly pure iron, in which the chief metalloid is manganese. Steel scrap has, of course, no direct oxidising effect on the molten iron, but will reduce its carbon, silicon, and phosphorus contents by dilution; its effect on the manganese depending on the percentage of manganese it contains. However, both silicon and manganese are subject to oxidisation in the refining process. Scrap melting, however, requires heat, and can only be done at the expense of refining, unless the mixer has capacity to spare.

COLD PIG IRON AND SCRAP PROCESSES.

Where cold pig iron and scrap are to be used, account should be taken of

1. The average analysis of the mixture.
2. The sand coating—if any—on the pig iron.
3. The oxidation of the charge in melting down.

The last item is somewhat variable and indeterminate, depending largely on the local furnace and melting conditions, and time taken in charging and melting down, &c. It may be assumed, however, that both pig iron and scrap are equally liable to oxidation by the flame, so that the whole charge should be dealt with on the same lines. Further, by analogy with reheating (mill furnace) practice, it seems probable that the Fe loss will range between 4 and 6 per cent.—say, 5·0 per cent. mean, and that the Fe thus lost will exist as the magnetic oxide, Fe_3O_4, containing approximately 72·5 per cent. Fe and 27·5 per cent. oxygen. The figures will then be approximately:

Loss in melting down (say) 5·0 per cent. of the total weight charged.
Equivalent, Fe_3O_4 = 7·00 per cent. (approximately).
Oxygen brought in = 1·90 ,, ,,

These assumptions and values may not be strictly correct, but they will serve as a basis for calculations, and will be found reasonably accurate.

1. *Acid Open-Hearth Process, with 50 per Cent. Hæmatite Iron and 50 per Cent. Scrap.*

The average analysis per 100 tons charged will be approximately:

Carbon	from	50	tons of	hæmatite	at	3·80	per cent.	= 1·90 tons	= 2·00 per cent.
„	„	50	„	scrap	„ (say)	0·20	„	= 0·10 „	
Silicon	„	50	„	hæmatite	„	2·50	„	= 1·25 „	= 1·30 „
„	„	50	„	scrap	„ (say)	0·10	„	= 0·05 „	
Manganese	„	50	„	hæmatite	„	1·00	„	= 0·50 „	= 0·80 „
„	;,	50	„	scrap	„ (say)	0·60	„	= 0·30 „	

Oxidation Table.—If the steel before tapping is to contain 0·20 per cent. carbon, 0·10 silicon, and no manganese, there will be oxidised per 100 tons charged:

Carbon . .	1·80 tons	requiring oxygen	= 2·40 tons	and producing	4·20 tons	CO gas
Silicon . .	1·20 „	„ „	= 1·37 „	„	2·57 „	SiO_2
Manganese .	0·80 „	„ „	= 0·23 „	„	1·03 „	MnO
Totals .	3·80 „	„ „	= 4·00 „	„	3·60 „	solids

Oxides.—Against this 4 tons of oxygen required, there is the 1·90 tons supplied by the melting down of the charge, leaving only 2·10 tons to be supplied by additions—equivalent to 2·10 ÷ 0·30 = 7·00 tons of Fe_2O_3. If supplied as ore containing 65 per cent. Fe and 3·0 per cent. SiO_2, the quantity required will be approximately 7·52 tons of ore, introducing 4·90 tons Fe and 0·22 tons of SiO_2.

Slag.—The total SiO_2 present is now:

	Tons.
SiO_2 Oxidised from the charge	2·57
Sand allowance at ¼ cwt.	0·62
Brought in by ore	0·22
Total	3·41

If the slag is to contain 50 per cent. SiO_2 the total slag make will be 3·41 ÷ 0·50 = 6·82 tons; made up as under:

SiO_2	3·41 tons	= 50·0	
MnO	1·03 „	= 15·1	
Al_2O_3, &c.		at 2·0	
FeO	2·25 „	= 32·9	(Fe = 1·75 tons)
Totals	6·82 „	= 100·0	

The Metallic Balance Sheet will be approximately as under:

Dr.	Metallic charge	100·00	*Cr.* Sand allowance	0·62
	Fe from ore	4·90	Metalloids oxidised	3·80
	Ferro alloys (say)	0·70	Fe (as oxide) in slag	1·75
			Mechanical losses Volatilised } (say)	2·00
			Yield—ingots and scrap	97·43
	Total	105·60	Total	105·60

Note.—The effect of adding lime or limestone—a more powerful base than FeO, and therefore permitting a higher percentage of SiO_2 in the slag—is important; and is well illustrated by the calculation of the slag as under. For a slag to contain 60 per cent. SiO_2 and 10 per cent. CaO, the total make of slag will be about 3·41 ÷ 0·60 = 5·69 tons; made up as under:

SiO_2	3·41	tons	=	60·0	
MnO	1·03	,,	=	18·1	
CaO	0·57	,,	at	10·0	(= 0·60 per cent. on the total charge)
Al_2O_3, &c.			,,	2·0	
FeO	0·56	,,	=	9·9	(Fe = 0·44 tons)
Totals	5·69	,,	=	100·0	

This indicates a saving in the loss of Fe as oxide in the slag of over 1¼ per cent. (a gain of over 1¼ per cent. in the yield), together with a 20 per cent. saving in the weight of slag made (and to be handled), which in itself should tend to increase the output of steel. It should be fed into the furnace when normally the first feed of ore would be given—thereby liberating the excess oxide in the slag—which method is found to give the best results in practice.

Acid Open-Hearth Process. Hœmatite Iron (M. Nos.) Scrap. Results per 100 *Tons Charged.*

Proportion of scrap used	33 per Cent.	50 per Cent.	67 per Cent.
Metalloids oxidised	4·87	3·80	2·73
Oxygen required	5·28	4·00	2·73
Less Fe_3O_4 made, oxygen equivalent	1·90	1·90	1·90
Oxygen required from oxides	3·38	2·10	0·83
Equivalent Fe_2O_3 (70 per cent. Fe)	11·30	7·00	2·77
Equivalent ore (at 65 per cent. Fe)	12·15	7·52	2·98
Fe introduced	7·91	4·90	1·94
SiO_2 introduced (at 3 per cent.)	0·36	0·22	0·09
Acids: SiO_2 from metal	3·43	2·57	1·72
SiO_2 „ sand allowance	0·62	0·62	0·62
SiO_2 „ ore	0·36	0·22	0·09
Total acids	4·41	3·41	2·43
Slag make (for 50 per cent. SiO_2)	8·82	6·82	4·86
Slag Analysis: SiO_2	4·41 = 50·0	3·41 = 50·0	2·43 = 50·0
MnO	1·12 = 12·7	1·03 = 15·1	0·94 = 19·3
Al_2O_3, etc.	at 2·0	at 2·0	at 2·0
FeO	3·12 = 35·3	2·25 = 32·9	1·39 = 28·7
Totals	8·82 = 100·0	6·82 = 100·0	4·86 = 100·0
Metallic Balance Sheet:			
Dr. Metallic charge	100·00	100·00	100·00
Fe from ore	7·91	4·90	1·94
Ferro alloys	0·70	0·70	0·70
Totals	108·61	105·60	102·64
Cr. Sand allowance	0·62	0·62	0·62
Metalloids oxidised	4·87	3·80	2·73
Fe (as oxide) in slag	2·43	1·75	1·08
Mechanical losses Volatilised } (say)	2·00	2·00	2·00
Yield—ingots and scrap	98·69	97·43	96·21
Totals	108·61	105·60	102·64

2. *Basic Open-Hearth Process, with 50 per Cent. Common Forge Iron and 50 per Cent. Steel Scrap.*

The average analysis of the charge—100 tons—will be:

Carbon	from 50 tons of	pig at	3·50 per cent.	= 1·75 tons	= 1·85 per cent.
,,	,, 50 ,,	scrap ,, (say)	0·20 ,,	= 0·10 ,,	
Silicon	,, 50 ,,	pig ,,	1·80 ,,	= 0·90 ,,	= 0·95 ,,
,,	,, 50 ,,	scrap ,, (say)	0·10 ,,	= 0·05 ,,	
Phosphorus	,, 50 ,,	pig ,,	1·50 ,,	= 0·75 ,,	= 0·78 ,,
,,	,, 50 ,,	scrap ,, (say)	0·06 ,,	= 0·03 ,,	
Manganese	,, 50 ,,	pig ,,	0·60 ,,	= 0·30 ,,	= 0·60 ,,
,,	,, 50 ,,	scrap ,, (say)	0·60 ,,	= 0·30 ,,	

Oxidation Table.—If the steel before tapping is to contain 0·20 per cent. carbon, 0·03 phosphorus, 0·10 manganese, and no silicon, there will be oxidised per 100 tons charged:

Carbon .	. 1·65 tons	requiring oxygen	= 2·20 tons	and producing	3·85 tons	CO gas
Silicon .	. 0·95 ,,	,, ,,	= 1·08 ,,	,,	2·03 ,,	SiO_2
Phosphorus	. 0·75 ,,	,, ,,	= 0·97 ,,	,,	1·72 ,,	P_2O_5
Manganese	. 0·50 ,,	,, ,,	= 0·15 ,,	,,	0·65 ,,	MnO
Totals	. 3·85 ,,	,, ,,	= 4·40 ,,	,,	4·40 ,,	solids

Oxides.—Against this 4·40 tons of oxygen required there is some 1·90 tons supplied by the oxidation of the charge in melting, leaving only 2·50 tons to be supplied by ore additions—equivalent to 2·50 ÷ 0·30 = 8·34 tons of Fe_2O_3. If supplied by ore containing 65 per cent. Fe and 3·0 per cent. SiO_2, the quantity required will be 9·0 tons of ore, introducing 5·84 tons of Fe and 0·27 tons of SiO_2. Where there is any appreciable quantity of P_2O_5 in the ore, or of SiO_2 and P_2O_5 in the lime, it should be taken into account here. The lime required may be roughly estimated in advance.

Slag Make, Lime, &c.—The total acids present now are:

		Tons.	
SiO_2	Oxidised from the charge	2·03	= 3·10 tons
	Sand allowance at ⅛ cwt. . . .	0·62	
	From ore, as above	0·27	
	,, lime, at 2·0 per cent. (say) . .	0·18	
P_2O_5.	Oxidised from the charge . . .	1·72	
	Total	4·82	

If the slag is to contain 28 per cent. acids, the total slag make will be 4·82 ÷ 0·28 = 17·20 tons, and the lime required to give 48.0 per cent. CaO in the slag will be 8·60 tons.

The slag analysis will be approximately as under:

	Tons		Per cent.
SiO_2	3·10 tons	=	18·0
P_2O_5	1·72 ,,	=	10·0
MnO	0·65 ,,	=	3·8
CaO		at	48·0
MgO		,,	5·0
Al_2O_3		,,	1·0
FeO	2·44 ,,	=	14·2 (Fe = 1·90 tons)
Totals	17·20 ,,	=	100·0

The Metallic Balance Sheet will be approximately:

Dr.		Cr.	
Metallic charge	100·00	Sand allowance'	0·62
Fe with oxides	5·84	Metalloids oxidised	3·85
Ferro alloys (say)	0·70	Fe (as oxide) in slag	1·90
		Mechanical losses Volatilised } (say)	3·00
		Yield—ingots and scrap	97·17
Total	106·54	Total	106·54

[*See* TABLE *on next page.*

3. *Basic Open-Hearth (Martin) Process, with 25 per Cent. Common Basic Pig and 75 per Cent. Scrap.*

The average analysis of the charge—100 tons—will be:

Carbon	from 25 tons of pig	at	3·20 per cent.	= 0·80 tons	= 0·95 per cent.
,,	,, 75 ,, scrap	,, (say)	0·20 ,,	= 0·15 ,,	
Silicon	,, 25 ,, pig	,,	1·00 ,,	= 0·25 ,,	= 0·32 ,,
,,	,, 75 ,, scrap	,, (say)	0·10 ,,	= 0·07 ,,	
Phosphorus	,, 25 ,, pig	,,	1·25 ,,	= 0·31 ,,	= 0·35 ,,
,,	,, 75 ,, scrap	,, (say)	0·06 ,,	= 0·04 ,,	
Manganese	,, 25 ,, pig	,,	1·20 ,,	= 0·30 ,,	= 0·75 ,,
,,	,, 75 ,, scrap	,, (say)	0·60 ,,	= 0·45 ,,	

Oxidation Table.—If the steel before tapping is to contain 0·20 per cent. carbon, 0·03 phosphorus, 0·20 manganese, and no silicon, there will be oxidised per 100 tons of charge:

Carbon	0·75 tons	requiring oxygen = 1·00 tons	and producing 1·75 tons	CO gas
Silicon	0·32 ,,	,, ,, = 0·36 ,,	,, 0·68 ,,	SiO_2
Phosphorus	0·33 ,,	,, ,, = 0·43 ,,	,, 0·76 ,,	P_2O_5
Manganese	0·55 ,,	,, ,, = 0·16 ,,	,, 0·71 ,,	MnO
Totals	1·95 ,,	,, ,, = 1·95 ,,	,, 2·15 ,,	solids

Oxides.—Against this 1·95 tons of oxygen required there is already 1·90 tons supplied by the oxidation of the charge in melting, so that no additions of ore will be required, nor will any Fe or SiO_2 be introduced from that source.

Basic Open-Hearth Process—50 per Cent. Pig Iron, 50 per Cent. Scrap. Results per 100 Tons Charged.

Pig Iron Used.	Hæm. (Spec.)	Com. Forge.	Com. Basic.	"Thomas."
Metalloids oxidised (tons)	2·68	3·85	3·47	4·22
Oxygen required	2·84	4·40	3·66	4·17
Less Fe_3O_4, equivalent oxygen	1·90	1·90	1·90	1·90
Oxygen required (as Fe_2O_3)	0·94	2·50	1·76	2·27
Equivalent Fe_2O_3	3·12	8·33	5·87	7·55
Equivalent ore (at 65 per cent. Fe)	3·36	9·00	6·32	8·14
Fe introduced	2·18	5·84	4·11	5·28
SiO_2 introduced (at 3 per cent. of ore)	0·10	0·27	0·19	0·24
Acids: SiO_2 from charge	1·18	2·03	1·18	0·64
sand allowance	0·62	0·62	0·62	0·62
from ore	0·10	0·27	0·19	0·24
,, lime	0·08	0·18	0·14	0·16
P_2O_5 ,, charge	0·07	1·72	1·42	2·57
Total acids	2·05	4·82	3·55	4·23
Slag make (at 28 per cent. acids)	7·33	17·2	12·7	15·1
Lime required (for 48 per cent. CaO)	3·66	8·6	6·3	7·5
Slag Analysis: SiO_2	1·98 = 27·0	3·10 = 18·0	2·13 = 16·8	1·66 = 11·0
P_2O_5	0·07 = 1·0	1·72 = 10·0	1·42 = 11·2	2·57 = 17·0
MnO	0·77 = 10·5	0·65 = 3·8	1·03 = 8·1	1·68 = 11·1
CaO	at 48·0	at 48·0	at 48·0	at 48·0
MgO	,, 5·0	,, 5·0	,, 5·0	,, 5·0
Al_2O_3	,, 1·0	,, 1·0	,, 1·0	,, 1·0
FeO	0·55 = 7·5	2·44 = 14·2	1·26 = 9·9	1·11 = 6·9
Totals	7·33 = 100·00	17·2 = 100·00	12·7 = 100·00	15·1 = 100·0
Metallic Balance Sheet:				
Dr. Metallic charge	100·00	100·00	100·00	100·00
Fe from ore	2·18	5·84	4·11	5·28
Ferro alloys (say)	0·70	0·70	0·70	0·70
Total	102·88	106·54	104·81	105·98
Cr. Sand allowance	0·62	0·62	0·62	0·62
Metalloids oxidised	2·68	3·85	3·47	4·22
Fe (as oxide) in slag	0·43	1·90	0·98	0·86
Mechanical losses / Volatilised } (say)	3·00	3·00	3·00	3·00
Yield—ingots and scrap	96·15	97·17	96·74	97·28
Total	102·88	106·54	104·81	105·98

Slag Make, Lime, &c.—The total acids present now are:

		Tons.	
SiO_2.	Oxidised from the charge	0·68	= 1·05 tons
	Sand allowance	0·31	
	From oxides	...	
	,, lime (say)	0·06	
P_2O_5.	Oxidised from the charge	0·76	
	Total	1·81	

If the slag is to contain 28·0 per cent. acids, the total slag make will be 1·81 ÷ 0·28 = 6·47 tons, and the lime consumption to give 48 per cent. CaO in the slag will be approximately 3·24 tons.

The composition of the slag will be approximately:

SiO_2	1·05 tons	=	16·3	
P_2O_5	0·76 ,,	=	11·7	
MnO	0·71 ,,	=	11·0	
CaO		at	48·0	
MgO		,,	5·0	
Al_2O_3		,,	1·0	
FeO	0·46 ,,	=	7·0	(Fe = 0·36 tons)
Totals	6·47 ,,	=	100·0	

The Metallic Balance Sheet will be approximately:

Dr.	Metallic charge	100·00	*Cr.* Sand allowance	0·31
	Fe from oxides	...	Metalloids oxidised	1·95
	Ferro alloys (say)	0·70	Fe (as oxide) in slag	0·36
			Mechanical losses Volatilised } (say)	3·00
			Yield—ingots and scrap	95·08
	Total	100·70	Total	100·70.

Basic Open-Hearth (Martin) Process—25 per Cent. Pig Iron and 75 per Cent. Scrap. Results per 100 Tons charged.

Pig Iron Used.	1.	2.	3.	4.	5.
	Hæmatite (M. Nos.)	Hæm. (Spec.).	Com. Forge.	Com. Basic.	"Thomas."
Metalloids oxidised (tons) .	2·13	1·56	2·12	1·95	2·31
Oxygen required . .	2·18	1·55	2·30	1·95	2·18
Less Fe$_3$O$_4$, equivalent oxygen	1·90	1·90	1·90	1·90	1·90
Net oxygen required .	0·28	nil (*excess* 0·35)	0·40	0·05	0·28
Equivalent Fe$_2$O$_3$ . .	0·93		1·33	...	0·93
Equivalent ore at 65 per cent. Fe . . .	1·00	Probably unworkable without a larger proportion of pig iron.	1·44	nil	1·00
Fe introduced . . .	0·63		0·94	,,	0·63
SiO$_2$ introduced (at 3 per cent. SiO$_2$) . . .	0·03		0·04	,,	0·03
Acids: SiO$_2$ from charge .	1·50		1·12	0·68	0·43
SiO$_2$ sand allowance	0·31		0·31	0·31	0·31
SiO$_2$ from ore .	0·03		0·04	...	0·03
SiO$_2$,, lime .	0·07		0·09	0·06	0·07
P$_2$O$_5$,, charge .	0·07		0·92	0·76	1·28
Total acids .	1·98		2·48	1·81	2·12
Slag Make (at 28 per cent. acids) . . .	7·08		8·86	6·47	7·54
Lime required (for 48 per cent. CaO) . . .	3·54		4·43	3·24	3·77
Slag Analysis: SiO$_2$.	1·91 = 27·0		1·56 = 17·6	1·05 = 16·3	0·84 = 11·0
P$_2$O$_5$.	0·07 = 1·0		0·92 = 10·4	0·76 = 11·7	1·28 = 17·0
MnO .	0·64 = 9·0		0·52 = 5·9	0·71 = 11·0	1·03 = 13·6
CaO .	at 48·0		at 48·0	at 48·0	at 48·0
MgO .	,, 5·0		,, 5·0	,, 5·0	,, 5·0
Al$_2$O$_3$.	,, 1·0		,, 1·0	,, 1·0	,, 1·0
FeO .	0·64 = 9·0		1·07 = 12·1	0·46 = 7·0	0·33 = 4·4
Totals .	7·08 = 100·0		8·86 = 100·0	6·47 = 100·0	7·54 = 100·0
Metallic Balance Sheet:					
Dr. Metallic charger .	100·00		100·00	100·00	100·00
Fe from ore .	0·63		0·94	...	0·63
Ferro alloys (say) .	0·70		0·70	0·70	0·70
Total . .	101·33		101·64	100·70	101·33
Cr. Sand allowance .	0·31		0·31	0·31	0·31
Metalloids oxidised .	2·13		2·12	1·95	2·31
Fe (as oxide) in slag .	0·50		0·83	0·36	0·27
Mechanical losses . } say Volatilised . . }	3·00		3·00	3·00	3·00
Yield—ingots and scrap	95·39		95·38	95·08	95·44
Total .	101·33		101·64	100·70	101·33

"DUPLEX" PROCESSES.

These processes are simple combinations of two standard processes—acid or basic, Bessemer or open-hearth—in which operations are carried a certain distance by one process and the refined metal transferred to another furnace to be finished. The oxidation of the various metalloids is as usual, and follows closely the diagrams and tables given in the standard works on steel—silicon and manganese being oxidised first, more or less simultaneously; followed by carbon; and by phosphorus if the slag be sufficiently basic. The leading object is to reduce the silicon in the first process, in order to reduce the slag make and increase the output of the finishing furnace, which, for the removal of the phosphorus, is necessarily a basic open-hearth furnace. Duplex processes apply therefore chiefly to phosphoric irons in districts where low silicon iron cannot be made without high sulphur, or where suitable oxides are scarce or unduly expensive, as compared with the iron itself; but they may also be used (if the iron is cheap enough) for the sake of large outputs, and the consequent economies in fuel, labour, and other charges, or to make rich phosphate slags from moderately phosphoric irons. They have great disadvantages as compared with the direct processes, such as double handling, plant, and losses, and an inherent tendency to produce over-oxidised steel, owing to loss of manganese in the first operation, resulting in low manganese in the finishing process. The cost of "blowing" in a converter, or of "washing" in an open-hearth furnace or mixer, can hardly be taken at less than 6s.—or 3s. 6d. per ton (pre-war levels)—whether it be recovered in the finishing process or not, which will largely depend on the amount of work already done on the iron.

There are three workable combinations worth considering in detail, namely, the acid Bessemer, basic Bessemer, and basic open-hearth (mixer) preliminary refining processes in combination with basic open-hearth finishing furnaces in each case. Each has its practical advantages and disadvantages. A storage and mixing vessel of some sort is a practical necessity wherever molten metal is used, though if no refining is to be done, it need be little more than a plain tank. An open-hearth mixer furnace of ample capacity combines this duty with that of desiliconising simultaneously in one furnace and at one handling. For a small output one large mixer furnace will do ; but generally, to ensure a regular grade of " washed " iron, two are preferable—the one filling up and desiliconising while the other feeds the finishing furnace, as with one only great irregularities are unavoidable, and may largely neutralise the benefit of refining. They should be of ample capacity and heating power ; for if not large enough, they cannot refine the iron sufficiently, and the finishing furnaces benefit but little. Two is the most economical number—more would be cumbrous—but they need not be limited in size, and can be used for melting scrap and cold pig also if larger than actually needed. On the other hand, a plant consisting of a simple storage mixer and one or two converters will handle more iron and do more work on it—at the expense of yield—for a smaller capital cost, and with greatly increased output from the finishing furnaces ; for the carbon is also partly oxidised—in fact, it can be blown if desired right down to the point where the metal is really a phosphoric steel, though with correspondingly high metallic losses. As a rule this is not desirable ; but in special circumstances it may pay to carry the process as far as possible, leaving only sufficient carbon to give the necessary boil for tapping heat in the finishing furnace. Another method is to blow the bulk of the charge down to this point, and add a single ladle of raw pig iron for finishing. This is probably the better method, for it introduces a limited amount of silicon and manganese as well as carbon, and should not only simplify finishing but improve the product. The process is very elastic and may be carried to one extreme or the other, either for output or economy as desired. Acid or basic lined converters may be used, FeO and MnO being the natural flux for SiO_2 in the former, as against burnt lime (CaO) in the latter, which therefore leaves the metal lower in silicon and higher in manganese (and metallic yield) than the acid converter, if not blown too far.

The choice between the mixer and converter methods of refining is essentially a question of yields, and of the relative value of the Fe unit as compared with the other charges (coal, wages, and other items chiefly affected by output) in any particular locality. The practical metallurgy is quite simple in either case.

Silicon, in the preliminary process, can be almost completely oxidised, but the benefit to the finishing furnace diminishes with each successive reduction. In mixer practice 0·20–0·40 per cent. silicon is generally considered low enough; but in the converter it is usually taken down to 0·10 per cent. silicon, or under.

Manganese is burnt out simultaneously and roughly in proportion to silicon, though more manganese remains in a basic than in an acid-refining process. The more there remains the better for the finishing furnace.

Sulphur is untouched in the acid converter, and remains virtually untouched under the comparatively siliceous slag of the basic converter or mixer, when oxidation has once begun. In the finishing furnace it is difficult to remove in the absence of manganese, and the iron should therefore be made low in sulphur in the blast-furnace—if necessary by raising the silicon. The whole benefit of desiliconising may be very largely lost in the finishing furnace in stewing out sulphur.

Phosphorus is of course untouched in the acid converter, and in the basic mixer or converter is hardly affected, provided the temperature be low, so that a comparatively siliceous slag can be carried. Even in the "Thomas" process it remains virtually untouched until all the other metalloids, including carbon, are almost completely oxidised, when the converter is turned down, more lime charged, and the phosphorus eliminated by the "after-blow." Practically the whole of the phosphorus is thus brought forward to the finishing furnace and a rich phosphate slag results, even from a common forge pig, if pure (low SiO_2) oxides are used.

Carbon.—So long as some silicon and manganese remain the carbon is not much affected, except that the graphitic carbon will be mostly combined—a considerable advantage to the finishing furnace—and it will usually remain between 2·50–3·00 per cent. In the converter it may be blown down to any extent, as already mentioned; but as we are mainly concerned here with material economy as compared with other processes, it may be taken as remaining at about 1·50 per cent., when the silicon has reached 0·10 per cent.

Slags.—The composition of slags from these refining processes must also be taken into account. Their composition will be controlled as usual by the normal finishing temperature of the processes, and suitable flux must be provided in proper quantity to produce them. The calculations are then quite simple; and the results are easily obtainable from the work done on the metal and the average analysis of the slag as run to waste. In the final operation they are the same as if the refined metal were received direct from the blast-furnace—modified only by the factor of yield—and the two results may be finally combined to give a true view of the whole operation.

DUPLEX PROCESS. I. ACID BESSEMER PRELIMINARY AND BASIC OPEN-HEARTH FINISHING FURNACE. FORGE IRON.

Oxidation Table.—If the "blown" metal is to contain 1·50 per cent. carbon, 0·10 silicon, 1·55 phosphorus, and 0·05 manganese, there will be oxidised per 100 tons of metal charged:

			Tons.		Tons.		Tons.	
Carbon	from 3·50	to 1·50	= 2·00	requiring oxygen	= 2·67	and producing	4·6	CO gas
Silicon	„ 1·80	„ 0·10	= 1·70	„ „	= 1·94	„ „	3·64	SiO_2
Phosphorus	„ 1·55	„ 1·55	= nil	„ „	= ...	„ „	...	P_2O_5
Manganese	„ 0·60	„ 0·05	= 0·55	„ „	= 0·16	„ „	0·71	MnO
Totals . .			4·25	„ „	4·77	„ „	4·35	to slag

Air Required.—To supply this 4·77 tons of oxygen by air-blast at 0·0290 tons of oxygen per 100 cubic metres—as before—there will be required at least 4·77 ÷ 0·0290 = 165 cubic metres of free air per ton of iron.

Slag.—If the slag is to contain 45·0 per cent. SiO_2 and 15·0 per cent. CaO, MgO, Al_2O_3, &c., the total slag make will be 3·64 ÷ 0·45 = 8·10 tons, made up approximately as under:

			Per Cent.	
SiO_2	3·64 tons	=	45·0	
MnO	0·71 „	=	8·8	
CaO	...		...	
MgO	1·21 „	=	15·0	
Al_2O_3	...		...	
FeO	2·50 „	=	31·2	(Fe = 1·95 tons)
Totals . . .	8·10 „	=	100·0	

N.B.—The burnt lime consumption will be approximately 15·0 per cent. × 8·10 = 1·21 tons, without which a lower SiO_2—

probably 40·0 per cent.—would be necessary, and the Fe loss as oxide would be considerably heavier. Raw limestone is more suitable for an acid converter, and the quantity required would be approximately 2·00 tons.

Yield.—The Metallic Losses and Balance Sheet are now approximately:

			Tons.
Dr. Metallic charge	100·00	*Cr.* Metalloids oxidised . .	4·25
Fe from oxides	nil	Fe (as oxide) in slag . .	1·95
Ferro alloys	nil	Mechanical losses Volatilised . . } (say) .	4·00
		Yield—refined iron	89·80
Total . . .	100·00	Total . .	100·00

Finishing Process.—The refined iron—as above—is now transferred to the basic open-hearth finishing furnace, and may be calculated out as usual—the necessary adjustment for the reduced weight of metal brought forward being dealt with in the final summary of the combined operations.

Oxidation Table.—If the steel before tapping is to contain 0·20 per cent. carbon; trace, silicon; 0·05 phosphorus, and no manganese, there will be oxidised per 100 tons of blown metal charged:

				Tons.		Tons.		Tons.
Carbon	from 1·50	to 0·20	=	1·30	requiring oxygen =	1·73	and producing	3·03 CO gas
Silicon	,, 0·10	,, nil	=	0·10	,, ,, =	0·11	,, ,,	0·21 SiO_2
Phosphorus	,, 1·55	,, 0·05	=	1·50	,, ,, =	1·93	,, ,,	3·43 P_2O_5
Manganese	,, 0·05	,, nil	=	0·05	,, ,, =	0·01	,, ,,	0·06 MnO
	Totals .	.		2·95	,, ,, =	3·78	,, ,,	3·70 to slag

Oxides.—In the form of Fe_2O_3 this oxygen represents 3·78 ÷ 0·30 = 12·6 tons, equivalent to 13·6 tons of ore containing 65 per cent. Fe; and will introduce 8·83 tons of Fe, and 0·41 tons SiO_2 (at 3·0 per cent. in ore).

Slag Make.—The total acids now present are:

	Tons.	
SiO_2 from the metal	= 0·21	} = 0·77 tons SiO_2
,, ,, ore	= 0·41	
,, ,, lime (say)	= 0·15	
P_2O_5 ,, ,, metal	= 3·43	
Total acids . . .	4·20	

If the slag contains 28 per cent. acids and 48 per cent. CaO, the total make of slag will be 4·20 ÷ 0·28 = 15·0 tons (requiring 7·50 tons of burnt lime), made up as under approximately:

			Per Cent.	
SiO_2	0·77 tons	=	5·2	
P_2O_5	3·43 ,,	=	22·8	
MnO	0·06 ,,	=	0·4	
CaO		at	48·0	
MgO		,,	5·0	
Al_2O_3		,,	2·0	
FeO	2·34	=	15·6	(= 1·22 tons Fe)
Totals	15·00 ,,	=	100·0	

Yield.—The Metallic Losses and Balance Sheet will be approximately:

Dr.		*Cr.*	
Metallic charge	100·00	Metalloids oxidised	2·95
Fe from ore	8·83	Fe (as oxide) in slag	1·22
Ferro alloys	0·70	Mechanical losses Volatilised } (say)	4·00
		Yield—ingots and scrap	101·36
Total	109·53	Total	109·53

Combined Results.—The net yield of ingots and scrap per 100 tons of original raw metal is:

0·898 × 101·3 = 91·0 tons.

The net consumption of ore is:

0·898 × 13·6 = 12·2 tons.

The net consumption of lime is:

1·21 tons in the converter
plus 0·898 × 7·50 = 6·74 ,, ,, finishing furnace
Total . . 7·95 ,, ,, two combined

The total make of slag is:

8·10 tons of waste slag from the converter
plus 0·898 × 15·00 = 13·47 ,, phosphate from the finishing furnace
Total . . 21·57 ,, the two together—of analyses as above

Note.—It is particularly interesting to compare these results with those from the same iron by the direct open-hearth and Bessemer hot metal processes.

DUPLEX PROCESS. II. BASIC OPEN-HEARTH (MIXER) PRELIMINARY, AND OPEN-HEARTH FINISHING FURNACE ON COMMON FORGE IRON.

Mixer Process: Oxidation Table.—If the "washed" iron contains 2·50 per cent. carbon, 0·30 silicon, 1·50 phosphorus, and 0·10 manganese, there will be oxidised per 100 tons of metal charged:

			Tons.		Tons.		Tons.	
Carbon	from 3·50	to 2·50	= 1·00	requiring oxygen	= 1·33	and producing	2·33	CO gas
Silicon	„ 1·80	„ 0·30	= 1·50	„ „	= 1·71	„ „	3·21	SiO_2
Phosphorus	„ 1·55	„ 1·50	= 0·05	„ „	= 0·06	„ „	0·11	P_2O_5
Manganese	„ 0·60	„ 0·10	= 0·50	„ „	= 0·15	„ „	0·65	MnO
Totals . .			3·05	„ „	= 3·25	„ „	3·97	to slag

Oxides.—To supply this oxygen in the form of Fe_2O_3 there will be required 3·25 ÷ 0·30 = 10·8 tons, equivalent to 11·6 tons of ore at 65 per cent. Fe, and introducing 7·55 tons of Fe and 0·35 tons SiO_2 (at 3·0 per cent. SiO_2 in ore).

Slag Make.—The total acids present now are:

	Tons.	
SiO_2 from the metal	= 3·21	= 3·66 tons
„ „ ore	= 0·35	
„ „ lime (say)	= 0·10	
P_2O_5 „ „ metal	= 0·11	
Total acids	3·77	

If the slag is to contain 40 per cent. acids and 45 per cent. CaO, the total slag make will be 3·77 ÷ 0·40 = 9·43 tons, and the lime consumption (at 96 per cent. CaO) will be 45 ÷ 96 × 9·43 = 4·40 tons.

The slag analysis will be approximately as under:

SiO_2	3·66 tons	= 38·8	
P_2O_5	0·11 „	= 1·2	
MnO	0·65 „	= 6·9	
CaO		at 45·0	
MgO		„ 3·0	
Al_2O_3		„ 1·0	
FeO	0·38	= 4·1	(= 0·29 tons Fe)
Total . . .	9·43 „	= 100·0	

Yield, &c.—The Metallic Balance Sheet will be approximately:

Dr. Metallic charge . . .	100·00	*Cr.* Metalloids oxidised . . .	3·05
Fe from ore	7·55	Fe (as oxide) in slag . .	0·29
Ferro alloys	nil	Mechanical losses Volatilised . . } (say). .	2·00
		Yield—refined iron . .	102·21
Total . . .	107·55	Total . . .	107·55

The refined iron—as above—is now transferred to the basic open-hearth finishing furnace, and may be calculated out as usual—the necessary adjustment for the difference in weight brought forward being made in the final summary of the combined results.

Finishing Furnace: Oxidation Table.—If the steel before tapping is to contain 0·20 per cent. carbon, 0·05 phosphorus, traces silicon, and manganese, there will be oxidised per 100 tons of "washed" iron brought forward:

				Tons.			Tons.			Tons.
Carbon	from 2·50	to 0·20	=	2·30	requiring	oxygen	= 3·08	and	producing	5·38 CO gas
Silicon	,, 0·30	,, nil	=	0·30	,,	,,	= 0·34	,,	,,	0·64 SiO_2
Phosphorus	,, 1·50	,, 0·05	=	1·45	,,	,,	= 1·87	,,	,,	3·32 P_2O_5
Manganese	,, 0·10	,, nil	=	0·10	,,	,,	= 0·03	,,	,,	0·13 MnO
	Totals	. .		4·15	,,	,,	= 5·32	,,	,,	4·09 to slag

Oxides.—If supplied as Fe_2O_3 this oxygen represents $5·32 \div 0·30 = 17·7$ tons, equivalent to 19·1 tons of ore at 65 per cent. Fe, and introducing 12·4 tons of Fe, and 0·57 tons SiO_2.

Slag Make.—The total acids present now are:

	Tons.	
SiO_2 from the metal	= 0·64	= 1·41 tons
,, ,, ore	= 0·57	
,, ,, lime (say)	= 0·20	
P_2O_5 ,, ,, metal	= 3·32	
Total . . .	4·73	

The total make of slag at 28 per cent. acids will be $4·73 \div 0·28 = 16·90$ tons, and the lime consumption for 48 per cent. CaO = 8·45 tons.

The slag analysis is approximately as under:

SiO_2	1·41	tons	=	8·3
P_2O_5	3·32	,,	=	19·7
MnO	0·13	,,	=	0·8
CaO			at	48·0
MgO			,,	5·0
Al_2O_3			,,	2·0
FeO	2·76	,,	=	16·2 (= 2·13 tons Fe)
Totals . . .	16·90	,,	=	100·0

Yield, &c.—The Metallic Balance Sheet will be approximately as under:

Dr.	Metallic charge	100·00	*Cr.*	Metalloids oxidised . .	4·15
	Fe from ore	12·40		Fe (as oxide) in slag . .	2·13
	Ferro alloys (say)	0·70		Mechanical losses Volatilised . . } (say) .	4·00
				Yield—ingots and scrap .	102·82
	Total . . .	113·10		Total . . .	113·10

Combined Results.—The net yield of ingots and scrap from 100 tons of the original raw metal is:

1·022 × 102·82 = 105·1 tons.

The total consumption of ore is:

	11·6	tons in the	mixer
plus 1·022 × 19·1 =	19·5	,, ,,	finishing furnace
Total . .	31·1	,, ,,	two together

The total consumption of lime is:

	4·40	tons in the	mixer
plus 1·022 × 8·45 =	8·65	,, ,,	finishing furnace
Total . .	13·05	,, ,,	two combined

The total make of slag is:

	9·43	tons in the mixer—to waste
plus 1·022 × 16·90 =	17·28	,, (phosphate) in the finishing furnace
Total .	26·71	,, of the two combined.

N.B.—Slag analyses as above.

DUPLEX PROCESS. III. BASIC BESSEMER PRELIMINARY AND BASIC OPEN-HEARTH FINISHING FURNACE. FORGE IRON.

In the early stages of the Bessemer basic process the silicon is more completely oxidised, and the manganese to a less extent than by the acid Bessemer process in blowing down to a given carbon, and the phosphorus remains practically untouched (until the after-blow). Assuming that the carbon is "blown" down to the same level as before—(by the acid converter)—that the slag is approximately the same as from the basic open-hearth mixer; and the metal when blown contains 1·50 per cent. carbon, 0·10 silicon, 1·50 phosphorus, 0·25 manganese, there will be oxidised per 100 tons of metal charged:

Oxidation Table.—

	Per Cent.	Tons.		Tons.		Tons.
Carbon	from 3·50 to 1·50 =	2·00	requiring oxygen =	2·67	and producing	4·67 CO gas
Silicon	,, 1·80 ,, 0·10 =	1·70	,, ,, =	1·94	,, ,,	3·64 SiO_2
Phosphorus	,, 1·55 ,, 1·50 =	0·05	,, ,, =	0·06	,, ,,	0·11 P_2O_5
Manganese	,, 0·60 ,, 0·25 =	0·35	,, ,, =	0·10	,, ,,	0·45 MnO
Totals . .		4·10	,, ,,	4·77	,, ,,	4·20 to slag

Blast.—To supply this 4·77 tons of oxygen by air-blast at 0·0290 tons of oxygen per 100 cubic metres of air—as before—

there will be required at least 4·77 ÷ 0·0290 = 165 cubic metres of free air per ton of iron.

Slag Make.—The total acids present now are:

	Tons.	
SiO_2 from the metal	= 3·64	= 3·73 tons
„ „ lime (say). . . .	= 0·09	
P_2O_5 „ „ metal	= 0·11	
Total	3·84	

If the slag is to contain 40 per cent. acids and 45 per cent. CaO, the total slag make will be approximately 3·84 ÷ 0·40 = 9·60 tons, made up as under:

SiO_2	3·73 tons	= 38·9
P_2O_5	0·11 „	= 1·1
MnO	0·45 „	= 4·7
CaO		at 45·0
MgO		„ 3·0
Al_2O_3		„ 1·0
FeO	0·61 „	= 6·3 (Fe = 0·47 tons)
Total . . .	9·60 „	= 100·0

N.B.—The lime consumption is 45 ÷ 96 × 9·60 = 4·50 tons.

Yield.—The Metallic Losses and Balance Sheet are approximately:

Dr. Metallic charge . . .	100·00	*Cr.* Metalloids oxidised . . .	4·10
Fe from oxides . . .	nil	Fe (as oxide) in slag . . .	0·47
Ferro alloys	nil	Mechanical losses Volatilised . . (say) . .	4·00
		Yield—refined iron . . .	91·43
Total . .	100·00	Total . .	100·00

The refined iron is now transferred to the basic open-hearth finishing furnace and dealt with as before; the overhead results being given in the final summary of the combined operations.

Finishing Furnace.—If the steel before tapping is to contain 0·20 per cent. carbon, trace silicon, 0·05 phosphorus, and 0·10 manganese, there will be oxidised per 100 tons of blown metal brought forward:

	Per Cent.	Tons.		Tons.		Tons.
Carbon	from 1·50 to 0·20	= 1·30	requiring oxygen	= 2·00	and producing	3·33 CO gas
Silicon	„ 0·10 „ ...	= 0·10	„ „	= 0·11	„ „	0·21 SiO_2
Phosphorus	„ 1·50 „ 0·05	= 1·45	„ „	= 1·87	„ „	3·32 P_2O_5
Manganese	„ 0·25 „ 0·10	= 0·15	„ „	= 0·05	„ „	0·20 MnO
Totals . .		3·00	„ „	= 4·03	„ „	3·73 to slag

Oxides.—To supply this oxygen in the form of Fe_2O_3, there would be required 4·03 ÷ 0·30 = 13·4 tons, equivalent to

14·45 tons of ore at 65 per cent. Fe, introducing 9·40 tons of Fe, and 0·43 tons SiO_2.

The total acids present now are :

	Tons.	
SiO_2 from the metal	= 0·21	= 0·78 tons SiO_2
,, ,, ore	= 0·43	
,, ,, lime (say) . . .	= 0·14	
P_2O_5 ,, ,, metal	= 3·32	
Total	4·10	

The slag make and lime consumption at 28 per cent. acids and 48 per cent. CaO would be :

Slag make = 4·10 ÷ 0·28 = 14·64 tons
Lime required = 48 ÷ 96 × 14·64 = 7·32 ,,

The slag analysis will be approximately :

SiO_2	0·78 tons	= 5·3
P_2O_5	3·32 ,,	= 22·7
MnO	0·20 ,,	= 1·4
CaO	.	at 48·0
MgO	.	,, 5·0
Al_2O_3	.	,, 2·0
FeO	2·38 ,,	15·6 (Fe = 1·77 tons)
Totals . . .	14·64 ,,	= 100·0

The Metallic Losses and Balance Sheet are approximately :

Dr. Metallic charge	100·00	*Cr.* Metalloids oxidised . . .	3·00
Fe from ore	9·40	Fe (as oxide) in slag . .	1·77
Ferro alloys (say)	0·70	Mechanical losses Volatilised . . (say) .	4·00
		Yield—ingots and scrap . .	101·33
Total . .	110·10	Total . .	110·10

Combined Results.—The net yield of ingots and scrap per 100 tons of original forge iron is :

0·9143 × 101·33 = 92·8 tons.

The net ore consumption (finishing furnace only) is :

0·9143 × 14·45 = 13·20 tons.

The net lime consumption is :

		Tons.
(1) In the converter . .	. . . .	= 4·50
(2) In the finishing furnace .	0·9143 × 7·32	= 6·68
	Total . .	11·18

The net slag make is:

	Tons.
(1) Ex-converter (to waste)	9·60
(2) Ex-finishing furnace (22·7 per cent. P_2O_5), 0·9143 × 14·64	13·36
Total	22·96

Effect of Slag Make on Output of Open-Hearth Furnace.

The capacity and output of a given furnace are largely affected by the incidental make of slag, and other conditions being equal, the yield of slag is a leading factor. It may be said that the true output of a furnace is not its make of steel alone, but its total make of steel and slag combined, for every ton of slag made absorbs so much effective heat which would otherwise be available for the metal. But it does not follow that a ton of slag is equivalent to a ton of steel production; it might well be either more or less. Slag affects make of steel in two ways. Not only are considerable heat units required to raise it to the final tapping temperature, but it is also a poor conductor of heat—often much inflated with non-conducting gases—floating on the surface and insulating the metal more or less effectively from the heat of the flame. Further, it is a relatively light and bulky material—in volume possibly several times its proportion by weight, so that it occupies a great deal of hearth room (thus reducing the capacity of the furnace) and forms a thicker insulation than its weight would indicate. Its heat contents will vary with its temperature and composition, but are probably considerably more than that of steel at the same temperature. The figures are estimated approximately by Professor Richards ("Metallurgical Calculation") at 450–550 calories for slag, as against 275–350 calories only for steel at normal tapping temperatures. It may be possible to find more exact values for these data, though it is of course impossible to fix an exact equivalent between steel and slag; but from continuous observations of furnace makes and lime consumption (the index of slag make), the author considers the figure may usually be taken at about 2·50 of steel to 1·00 of slag. In other words, if the normal slag make be reduced by 1·0 per cent. (say 10 tons) the steel make will be increased by about 2·50 per cent.

(25·0 tons) and *vice versa,* other conditions remaining the same. The last point is important; for it obviously will not do to compare different practices together on this basis. For instance, hot metal practice cannot be compared with cold pig and scrap practice even in the same furnace; for the physical conditions are entirely different in the two cases, and a different standard is required for each. Similar practices only should be compared together, when the above ratio will usually be found pretty near the mark.

Any improvement in quality of materials (of which pig iron is the most important) or in practice resulting in reduced slag make (or lime consumption) will be found to have an effect on steel production out of all proportion to the difference made—due to the fact that there is not only less slag to be raised to tapping temperature, but a thinner layer of it to be penetrated by the heat.

Excessive slag is therefore not only a nuisance when tapping, but a serious hindrance to output and economy. The effect of output on costs need hardly be emphasised, nor the advantage of cheap iron, provided output is maintained (for any extra consumption of oxides is recovered in the form of increased yield, and the difference in lime is only trifling); but if output is reduced to any great extent the inevitable increase in other costs will largely counterbalance or even outweigh the initial advantage. In the "Martin" process, with only 20 to 30 per cent. of pig iron, no great differences need be expected in any direction; but with 40 to 50 per cent. of pig they are appreciable; and serious with 75 to 100 per cent. of iron when its quality and yield of slag are most important if its advantage in price is to be realisable. In such cases, however, control of a blast-furnace plant is usually involved, and molten metal is supplied to the steelworks with considerable labour-saving in both departments. The steel furnaces are also saved the melting of the iron, but the results are often disappointing in output and cost on account of the poor quality of iron supplied and its large yield of slag. It is interesting here to compare the various basic open-hearth processes as regards slag make per ton of steel, and the various methods of dealing with it. In the "Martin" process it only amounts to 5 to 10 per cent. by weight on the charge—the rapidity of the process being mainly due to this fact and the consequently short boiling and finishing period.

With 50 per cent. of pig iron, it varies between 10 to 20 per cent. according to the quality of the iron, and output is relatively low; and with larger proportions up to 100 per cent., as in hot metal processes, it may rise to 30 per cent. or even more, and the

General Summary of Results.

Direct Hot Metal Processes.	Bessemer.				Talbot Basic Open-Hearth.				
	Acid.		Basic.						
	Hæmatite (M. Nos.).	Hæma-tite (Spec.).	Common Forge.	"Thomas."	Hæmatite (M. Nos.).	Hæmatite (Spec.).	Common Forge.	Common Basic.	"Thomas."
Lime	...	...	13·5	11·3	11·5	5·0	15·2	10·5	13·0
Oxides	...	...	...	...	28·2	19·1	30·8	25·1	28·8
Yield	86·4	89·9	84·7	86·0	106·6	103·7	106·1	105·0	106·3
Slag make	7·9	3·3	26·0	21·8	22·9	10·1	30·4	20·9	25·9
„ P_2O_5 per cent.	...	...	13·2	23·1	...	...	11·3	13·2	19·5

Duplex Hot Metal Processes. (Common Forge).	Preliminary.			Basic Open-Hearth Finishing Furnace.			Combined.		
	Mixer.	Acid Bess.	Basic Bess.	Mixer.	Acid Bess.	Basic Bess.	Mixer.	Acid Bess.	Basic Bess.
Lime	4·4	1·21	4·5	8·45	7·5	7·3	13·0	8·0	11·2
Oxides	11·6	...	...	19·1	13·6	14·45	31·1	12·2	13·2
Yield	102·2	89·8	91·4	102·8	101·3	101·3	105·1	91·0	92·8
Slag make	9·4	8·10	9·6	16·9	15·0	14·6	17·3	13·5	13·4
„ P_2O_5 per cent.	1·2	...	1·1	19·7	22·8	22·7	19·7	22·8	22·7

General Summary of Results—(continued).

Scrap Processes.	Acid Open-Hearth.			Basic Open-Hearth with 50 per Cent. Scrap.				Basic Open-Hearth (Martin) with 75 per Cent. Scrap.				
	One-third Scrap.	One-half Scrap.	Two-thirds Scrap.	Hæmatite Special.	Common Forge.	Common Basic.	"Thomas."	Hæmatite (M. Nos.).	Hæmatite (Spec.)	Common Forge.	Common Basic.	"Thomas."
Lime	...	...	...	3·7	8·6	6·3	7·5	3·5	Unworkable.	4·4	3·2	3·8
Oxides	12·1	7·5	2·3	3·4	9·0	6·3	8·1	1·0		1·44	...	1·00
Yield	98·7	97·4	96·3	96·1	97·2	96·7	97·3	95·4		95·4	95·1	95·4
Slag make . . .	8·8	6·8	4·8	7·3	17·2	12·7	15·1	7·1		8·8	6·5	7·5
" P_2O_5 per cent.. .	...	...	...	1·0	10·0	11·2	17·0	...		10·4	11·7	17·0

Note.—These figures all have reference to the *charged* weight—not to the *finished* product—for which they must be divided by the yield in each case.

process is unworkable unless it can be removed. This should be done as early as possible, both to expedite operations and for the effect on further additions which are otherwise greatly diluted. It can be done quite simply by the use of a tilting furnace, as in the Talbot process, and the bulk of the slag run off over the fore-plate notches when ready ; but tilting furnaces are very expensive plant, and they also introduce various special difficulties and expenses in connection with movable ports, chills, and water-cooling, &c. In the Bertrand-Thiel process two fixed furnaces are employed and the metal is transferred from one to the other at an intermediate stage, the first slag being separated from the metal during the transfer, so that the finishing furnace is not hampered with an excess. This involves double plant, handling, labour, and losses of time and metal, &c., and is in effect a " duplex " process. In the Hoesch modification one furnace only is used, the whole charge being tapped out at an intermediate stage, the slag and metal separated and the refined metal poured back into the same furnace to be finished. This also must be classed as a duplex process. In the Monell process a single furnace (basic open-hearth) is used, into which the lime, oxides, and scrap are charged and strongly heated before the molten metal is charged, and advantage is taken of the violent reaction which then occurs to let the slag boil over and run to waste. Such slag can only be half-spent, and carries off a great deal of free lime and oxide (sometimes up to 60 per cent. FeO), which must subsequently be made up by fresh cold additions, unless sufficient excess was originally charged. Where the iron unit is cheap enough such waste may not be serious, though nothing could be technically more inefficient, and personally, the author would prefer a Bessemer duplex plant. Fixed furnaces with two tap holes have also been tried for working molten metal, but were not very successful, as they also do not provide properly for removal of excess slag—the first condition of all hot metal open-hearth processes. In the various so-called duplex processes also, the first object is to refine the raw metal sufficiently to relieve the finishing furnaces of excess slag. Such preliminary refining may be considered as essentially part of the steel-making process and taken into the cost of conversion ; or its cost may be charged on to that of the pig iron, with the same final effect ; the result in either case proving that hot metal even of good quality is always costly to convert and requires much expensive plant, unless some simple means of getting rid of slag is found.

To this end the author has recently patented an improved process (No. 116663) for removing slag from fixed furnaces by blowing it off, whereby all the advantages of a tilting furnace are secured without its expense and upkeep; and a single inexpensive plant suffices for any number of fixed furnaces, making them equivalent to the like number of tilting furnaces. He hopes to lay further particulars before the Institute in due course.

Operating Orders.

In ordinary routine work there are many directions where such calculations are useful, of which the first is in the working of the furnace or converter. The quality of materials will, of course, vary within limits; but the calculated figures can be translated approximately into operating orders in terms of tons or charging boxes, and will be approximately realised over a period if the data are correct and the practice steady, though not always on individual charges. Standing orders for charging and preliminary additions must be drawn up with care, and should be strictly observed, but the "feeding" quantities and finishing operations must be left to the discretion of furnacemen. For this reason, and also to allow for irregularities, the preliminary additions (lime and oxides) charged should be below the calculated quantities, leaving the men a reasonable margin to work in for finishing. Regularity in every direction is a first condition for output, economy, and quality; and on these lines the men can be guided straight into the right groove and the practice standardised. The same applies if any change of practice is necessary or if conditions are suddenly altered in any important direction, and the change can be made quickly and smoothly without a long interval of floundering and mistakes. It is surprising how quickly workmen fall into a groove, and how slow they are to get out of it, without assistance.

PHOSPHATE SLAGS.

Another use of this method is its application to the problems of phosphate slag production. The possibility of making saleable slags from any pig iron, their probable P_2O_5 contents, probable quantity and value per ton of ingots—or of pig iron—and the conditions for maximum results, &c., can all be determined with ease, provided allowance for the extra SiO_2 received from the furnace brickwork is not overlooked. It frequently happens that the P_2O_5 is too low to fetch a reasonable price—or indeed anything—for the slag. The P_2O_5 unit also fetches a higher price in concentrated than in dilute form, for a rich slag costs no more to grind, bag, and deliver than a poor one. It is therefore to the steel-maker's advantage to produce as rich a slag as he can. Opinions on how to do this, or whether it is worth while, vary considerably—whether to reduce the silicon or raise the phosphorus of the iron, or to add phosphoric ores or lime in the steel furnace—and as to the effect of such steps on the output of steel and the quantity, make, and value of the slag.

These problems are rarely reduced to reasoned figures, and anything, or nothing, may be done; a common conclusion being that the output of steel must suffer, or, as frequently expressed, "You can't make steel and make slag." The fallacy of this view can be exposed immediately, and the calculations not only show clearly what the probable effects will be, but bring out the fact that the simplest way to raise the P_2O_5 is to reduce the amount of SiO_2 present (*i.e.* the make of slag)—a step which naturally increases the output of steel from the open-hearth furnace. The real facts are that steel cannot be made at all without making slag, and that the more the slag make is reduced the richer it will be, and the greater the output of steel. On these lines the conditions for higher-grade slags and maximum output of steel are not opposed to each other, but are identical. Extraneous SiO_2 from all other sources must first be cut down, but the silicon of the iron remains the chief source. When this also is down to its lowest, the output of steel and quality of slag will both be at their highest, provided the total acids are not below the normal 28 per cent. standard. If they fall much below this level—say to 21 per cent.—the slag make is needlessly great and the P_2O_5 unduly low; in this case only three-fourths of what they might be, indicating considerable room for improvement in the open-hearth practice. This condition has already been referred to in connection with the removal of sulphur. There is also the possibility of desiliconising the metal by preliminary refining (or some form of Duplex process), whereby the ratio of silicon to phosphorus is reduced, and a smaller weight of higher grades produced from the finishing furnace. The other methods, such as introducing extra phosphorus into the iron, or with the lime and oxide additions, are wrong in principle; for they must result in increased make of slag and reduced output of steel, and are rarely worth while. They also show the effect of using a proportion of scrap, on which some misconception often exists. Steel scrap virtually does not affect the composition of the slag at all, for it needs no lime nor oxide—in fact, it provides oxide free from SiO_2. The only thing it really affects is the quantity of slag made, not its composition, which depends chiefly on the proportion of silicon to phosphorus in the pig iron. There is no need now to consider the question of citric solubility and the effects of fluorspar, &c., beyond noting that this test is now virtually abandoned. Expert agricultural opinion is about equally divided as to the relative fertilising values of so-called "soluble" and "insoluble" slags, from which it appears that there is little to choose between them. It is also found that the phosphoric acid is ultimately soluble in either case, both by this test and in the soil; the chief difference being in point of time, which is not specified by nature. Originally a German invention, it favoured their own high-grade "Thomas" slags at the expense of the poorer open-hearth products; but the test is now found inappropriate and is largely discredited, if not finally abandoned. As, however, prejudice dies hard, steelmakers should, the author thinks, take concerted action to have it finally abolished, both in their own and in the national interest.

"GENERAL" QUALITY OF STEELS.

Some reference is necessary to the comparative quality of steels by the various standard processes—a subject on which there are wide differences of opinion; for every maker naturally upholds his own product and process. The term "general quality" is expressly used to distinguish liability to physical defects from composition and mechanical behaviour—or "particular" quality. "General" quality is the subject of inspection; and as physical defects are—or should be—all caught, cut out, and rejected by the works staff and official inspectors before despatch, the question between processes is resolved into one of comparative yield of sound steel from the ingot—*i.e.* of costs. Let it be granted at once that steel can be, and is, made as sound, or as poor, by one process as by another; that, subject to tests and inspection, the most exacting engineers are perfectly satisfied with continental "Thomas" and "Martin" steels for almost every purpose; that prejudice against one process is largely due to the self-interest, &c., of makers by some other process: and the fact again emerges that, omitting prejudice, the question is really one of management and cost. The author always holds that, when properly understood and handled, as good a yield of sound steel from the ingot can be realised by one process as by another. Over-oxidation is mainly responsible for physical defects, and is unavoidable in all processes; but though some are more liable to it than others, it can be kept within limits, and is rectifiable by suitable measures. There is no occasion to go deeply into this difficult and controversial subject here; but it may be admitted that the Bessemer converter is not under such sensitive control as the open-hearth furnace, and that acid processes are less liable to over-oxidation than basic. Of these the "Thomas," "Martin," and Duplex processes are most liable to over-oxidation, and therefore most in need of careful management; but the fact remains that, given proper handling and regular conditions, good yields of sound steel can be—and are—regularly obtained by these processes abroad, if not in this country. Abroad some method of deoxidising is usually adopted as a regular practice in these highly oxidising processes, and every cast is deoxidised as a precaution, whether necessary or not. The secret of their success is largely in their use of manganese in restraint of this tendency, by substituting MnO for FeO (MnO displacing FeO) in the slag. German "Thomas" irons are normally made to contain about as much manganese as silicon and phosphorus together; and for the "Martin" process, special irons are made containing up to 5 per cent. manganese, failing which, spiegel is put in with the charge to make up the deficiency. In ordinary basic open-hearth practice, it is desirable that the steel just before tapping should contain 0·15 to 0·25 per cent. residual manganese, which usually corresponds with 6 to 8 per cent. MnO in the slag, if in good order. Less than this amount usually indicates over-oxidised—or "wild"—steel; while more apparently tends to restrain the boil and delay the furnace. To give 8·0 per cent. MnO in the slag plus 0·20 per cent. residual manganese in the steel, or equivalents, the average manganese of the charge should be not less than $\frac{1}{2}$ (Si + P) + 0·20 per cent., which formula illustrates another useful application of this method.

Deoxidising should be commenced in the furnace or converter and completed in the ladle before ever the steel reaches the ingot moulds; and the author prefers to see at least 0·02 per cent. of silicon or phosphorus in the finished steel as a guarantee against this fault and the risk of brittleness and unaccountable failure under shock occasionally found, in their absence, in material which has passed all the usual mechanical tests.

In conclusion, the author hopes that this paper will be of general use, and that the Institute will give it a sympathetic reception.

DISCUSSION.

Mr. B. **Talbot**, Member of Council, said that, as a steelmaker, he congratulated Mr. Bagley on producing a most excellent paper, which would be not only of general use, but of specific use in the open-hearth shops of Great Britain to superintendents, to sample passers, and to intelligent furnace-men alike, all of whom desired to understand what was really going on in their furnaces. Mr. Bagley had produced a balance-sheet in which he had indicated what it might be hoped to obtain from theoretical calculations. It would be most interesting to see how the practical shop results varied from the estimated yields so calculated. Personally, he thought Mr. Bagley was very near shop results. One of the most interesting comparisons was that made between direct metal processes and combined duplexing. There was seen to be an enormous difference in the yields. In the one case Mr. Bagley had taken his (Mr. Talbot's) own process, on which he had made his calculations. In another he had taken a continuous preliminary refining, and the results were closely comparable, but in regard to duplexing where the yield was 91 or 92 per cent., against possible yields by the direct metal processes of 105 (which were obtained), it had to be admitted that, by paying for the ore, there was an enormous difference. What he could not understand was the practice in the United States. His own process in the United States was very largely used, millions of tons being made by it; but in every case of which he knew—unless the practice had ceased since the war—Bessemerised metal was used in the 200-ton tilting-furnaces, and obviously the yields must be very different. Why that was done he could never understand, unless the profit was so large that they could afford to put the cost up in order to get the profit on the increased output. That could not be done in Great Britain. The other point he noticed was Mr. Bagley's reference to tilting-furnaces. He (Mr. Talbot) had had experience in designing tilting-furnaces for the best part of twenty years, and for fifteen years previous to that he had been concerned with the designing of fixed basic open-hearth furnaces, and he could say as far as his experience went it took a period of twenty years before even a satisfactory fixed basic open-hearth furnace was evolved, suitable for working as it was worked to-day. He did not understand why makers seemed so nervous in regard to tilting-furnaces. With liquid metal he would venture to predict that it would be the furnace of the future and that its size was capable of very great expansion, although it had already expanded from 50 or 60 tons to about 250 tons in about fifteen years. For that reason he could not follow Mr. Bagley's suggestion that by blowing the slag off a fixed furnace all the advantages of the tilting-furnace were obtained. Personally he would not care to handle a furnace of 400 tons capacity, such as he had in mind he might live to see with a fixed hearth. He would certainly want a tilting body so that he could deal with the metal as he required it.

Mr. F. W. **Harbord**, C.B.E., Member of Council, congratulated the author on his very interesting and important paper. He said there was nothing more important in the steel industry than that balance-sheets showing the possible and actual yield should be regularly got out, and it was very important that the man who was actually operating the furnace should have some simple method of arriving at what his actual results were. The method given by the author was certainly sufficiently approximate to enable the ordinary furnaceman to know what he ought to get from his day's work, or at all events from his week's work, and then to compare it with what he was actually getting, without waiting for the records from the office giving the yields which were obtained later on. When in the States some years ago, he found that the average intelligent open-hearth man was accustomed to ask for the analysis of his slag, so that he might know exactly how much oxide of iron the finishing slag contained. In one works each furnaceman was given an analysis of the slag with the percentage of oxide of iron, lime, and silica, so that he might see exactly what was the composition of the finishing slag. A balance-sheet on the basis suggested by the author told exactly what was possible, and although that could not be obtained in everyday practice, it could be aimed at, and it stimulated the whole of the works' staff, and tended to produce economy and efficiency. There was one point which was incidentally brought out in the paper, which was very important from a basic steel point of view, and that was the great advantage of making a real basic pig in the blast-furnace, low in silicon and containing a fair amount of manganese, so that as little work as possible was thrown on the open-hearth furnace. It had two advantages. If there was the proper amount of manganese it assisted the work all through by preventing over-oxidation, and if there was low silicon it meant a lower bulk of slag, which not only facilitated the operation but incidentally gave a high phosphoric slag with a lower consumption of lime. In the present days of high costs, and when efficiency was of such vital importance, those things might make all the difference between a profit and a loss. If one could reduce the bulk of the slag by having low silicon in the pig iron, and so obtain a credit of an extra two shillings per ton for the slag, it was a very important matter. He congratulated the author on his paper, which if placed in the hands of the workmen would give them a most useful method of controlling their furnace work.

Mr. T. **Twynam** (Middlesbrough) congratulated the author on his able paper. It was the first time a clear comparison of various steel-making processes had been committed to paper. The method of taking 28 per cent. acid in the slag seemed a very good one, as it enabled a calculation to be made which was otherwise practically impossible. When the Talbot process was introduced the question of the slag had been a very important one indeed, and slag, of course, was not made then which compared with the slag given in the paper. The possibility of making a slag with such a high percentage of phosphoric acid as that given, 22 per cent., put quite a different complexion on the matter, especially as the question of citric solubility had now become obsolete. It had always been to a certain extent a drawback to open-hearth phosphoric processes that the citric solubility of the phosphoric acid in the slag had been looked upon as an essential point.

Professor T. TURNER (Birmingham University) was glad to see that Mr. Bagley in his paper paid so much attention to the question of the quality and quantity of the slag in the steel-making processes. He (Professor Turner) had ventured a number of years ago, in discussing the question of the puddling process before the Institute, to point out how important the slag was in any iron purification process.[1] It was not desired to attack the furnace bottom, but it was desired for that to remain permanent. The effect of the air when the metal was once melted down and covered with slag was almost negligible, so that the reactions depended almost entirely on the slag which was present. He knew that some old metallurgical books defined slag as smelter's refuse. He would be inclined to say that slag was the smelter's friend, provided, of course, it was of the right composition. Mr. Bagley pointed out the disadvantages of too much slag, and its blanketing effect owing to its being a non-conductor; he had also referred to the high specific heat of slag, as a result of which there was a considerable consumption and waste of heat if too much slag were produced. On the other hand too little slag was an equal disadvantage. The slag had to be of the right texture and the right fluidity, so that it could act freely on the metal and could be freely tapped. Hence a test of the slag, from time to time, such as had been indicated by Mr. Harbord, was of the greatest importance. With reference to the active oxide of iron present in the slag, he had always adopted the view put forward by the late Sir William Siemens, that the oxide was present in the form of magnetic oxide. He thought that was now generally accepted, and much evidence in favour of that view could be obtained by examination of the cooled slags by the microscope, when very beautiful and distinct examples of the crystallised magnetic oxide from the slag were found. Magnetic oxide was the one which gave the greater fluidity, and that fluidity was necessary for the proper conduct of the process. Again, the proper composition of the slag might have a very important effect on its value, as had been indicated, so that when something in the neighbourhood of 20 per cent. of phosphorus was obtained in basic slag, a material was produced which was far more valuable in proportion to the phosphorus present than one which had a lower percentage. There were many other interesting points in the paper. He believed it dealt with principles which were really fundamental for the proper conduct of a steel-melting process.

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[1] *Journal of the Iron and Steel Institute*, 1891, No. I. p. 119.

Dr. J. E. **Stead**, F.R.S., Vice-President, said he had not had time to check all the wonderful calculations given by Mr. Bagley, but he thought they might be accepted as being correct. The paper was of immense value, especially to students, and he strongly recommended them to study it, and also to check the calculations. Having checked the calculations, they would acquire a better notion of the results than by simply accepting the figures given. Some reference had been made to the desulphurising of iron. In that connection he thought the originator's name should be mentioned. Until Mr. Saniter had started on the desulphurising of iron, it had been assumed that it could not be worked with a basic open-hearth furnace. He complimented Mr. Bagley upon having given such valuable information.

CORRESPONDENCE.

Mr. J. E. **Fletcher** (Dudley) wrote that Mr. Bagley's contribution would be invaluable to steel metallurgists. The data tabulated were in themselves a most useful addition to technical literature, especially the information as to the analyses of the slags and the comparisons of the slag produced per ton of yield and of metal charged. In considering the yield and wastes in open-hearth processes he (Mr. Fletcher) had elsewhere[1] pointed out that the higher yields accompanied small slag make and, in basic processes, when the slag produced was richest in phosphates and poorest in iron, not only was the thinner slag blanket a better conductor of heat to the bath, but its function in refining and alloying was speeded up when superheated above its true melting temperature.

The utility of high MnO content in the slag as a displacer of FeO was very great, and had had, generally speaking, greater recognition on the Continent than here. During the making of manganese steel in the basic open-hearth (the manganese being added through the slag) he (Mr. Fletcher) had had much experience of the behaviour of CaO.MnO slags, and thoroughly agreed with Mr. Bagley in the need for residual manganese in basic (and acid) steels before adding the finishing, as a proof of satisfactory deoxidation before tapping. If such a safeguard were commonly practised, the evils attaching to oxide evolution in the ladle and in the ingots would largely be overcome. He (Mr. Fletcher) from his own experience believed thoroughly in the removal of slag at the proper moment and in the addition of molten basic slag poor in phosphorus in the duplex process, and he hoped for the complete success of Mr. Bagley's process of blowing off the slag from fixed furnaces. A speeding up of the process should result.

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[1] "On the Yields and Wastes in Open-hearth Furnaces," *Journal of the Staffordshire Iron and Steel Institute*, 1915.

Dr. F. Rogers (Sheffield) wrote welcoming the paper for its balanced attitude towards the relation of technical and commercial features in steel-making. The author quite frankly recognised the importance of quality, and the super-importance of oxidation as a source of defects; and the relative limitations of the several processes in those respects were, he considered, fairly stated. From that point onwards he was at one with the author in regarding production, particularly of the classes of steel which the author had in view, as the dominating factor, and that was undoubtedly worthy of such full systematic chemical control as he maintained. Any neglect of such system to the fullest possible extent in manufacturing operations generally, spelt inevitable losses, even though they might pass unsuspected at the time. The next application of what was at one time mere ultra-science would be the equally precise control of temperature at the various stages; temperature control in steel-making being still somewhat crude, even though it were known that some of the reactions were reversible with change of temperature under conditions which could and sometimes did occur in practice—for example, the phosphorus and sulphur reactions in the basic open-hearth and electric, and silicon in the acid open-hearth processes. Basic and acid metallurgists were as yet only vaguely learning how to remove the conditions as far as possible from the reversal zones, in order to get the greatest possible speed of working. Practical quantitative control, therefore, not only of the chemical, but likewise of the simultaneous physical conditions in steel-melting, was, he believed, sure to be realised in the not far distant future.

B. Yaneske (Sheffield) wrote that Mr. Bagley's system of calculating the consumption of materials by various methods of steel manufacture was very useful, but in connection with open-hearth furnaces he (Mr. Yaneske) thought that an allowance ought to be made for the large amount of oxidation of the metalloids effected by the action of the furnace gases. The amount of oxygen supplied in that way might reach 50 per cent. or even more of the total oxygen required to oxidise the carbon in ordinary acid open-hearth practice using cold pig iron and scrap. That reduced considerably the amount of iron ore required, and therefore the weight of iron derived from the ore. The figures for the yield of ingots and scrap would be much lower in practice than were obtained by Mr. Harvey's calculations in which gas oxidation was ignored.

Mr. C. H. F. **Bagley**, in reply to the discussion, regretted that the paper had not produced a fuller criticism of the principles advanced, in view of the originality of the whole system; but it was most satisfactory that it had received such general assent from the leading authorities on the subject—to whom he tendered his hearty thanks for all their complimentary remarks.

There was little to reply to, except that some doubt had been expressed as to whether the calculated yields were realisable in everyday practice, and whether the results in general were not more theoretical than practical. It should be noted that the item of "Yield" in the balance-sheets as drawn covered both ingots and scrap—including all skulls, butt ends, and pit scrap, etc., whereas, normally, cost sheets showed the nett yield of ingots only. The reason for that was that those items varied considerably in different works—possibly up to 3 per cent.—without it being in any way the fault of the process employed. Subject to that adjustment, the results were really more accurate than was at first appreciated, and would be found to correspond very closely with actual results wherever the data and practice followed were the same as had been assumed. That was confirmed by actual figures he had had for various practices from English, Continental and American works taken from actual costs. It was, of course, obvious that if practice or materials varied from the data assumed in any important respect, the results throughout would be different; for the whole sequence was affected, and a fresh calculation had to be made. For instance, in the basic O.H. (Talbot) process, if 30 per cent. of scrap were used and only 70 per cent. of pig iron, there was only 70 per cent. of the weight of metalloids to be oxidised and of products formed. The oxides required were less than 70 per cent. for the preliminary heating of the scrap made a certain amount of Fe_3O_4, thus further diminishing the quantity to be added; and also the Fe and SiO_2 introduced (with consequent effect on the slag make and lime consumption) and considerable disturbance to the balance-sheet. (N.B.—With pure ores the slag analysis is hardly affected.) In such a case the gross yield would fall to 100–102 per cent., as might be verified by recalculation, or from actual results.

Mr. Yaneske pointed out that flame oxidation was often important and might account in the acid O.H. process for 50 per cent. or more of the total oxygen supplied, which, of course, was quite correct—in fact it might reach 100 per cent. or more, as in the "Martin" process; but allowance had already been made in all the calculations of scrap processes of 1·90 units of oxygen—which he (Mr. Bagley) gathered Mr. Yaneske considered was insufficient. The point was already noted in the paper, both as regarded hot metal and scrap processes (pp. 149, 161, 162, *et seq.*), in which it was shown that some flame oxidation was inevitable by all O.H. processes, and not only during the melting down period but even afterwards when the bath was molten and covered with slag—though if the heat were good that was almost negligible—as Prof. Turner remarked. In a keen furnace with a charge of molten iron only, the full calculated quantity of oxides was often actually required and the calculated yield was commonly realised; but clearly, if for any reason it was not taken or not fully utilised, the final yield would suffer and the result appeared in the balance-sheet.

Further to the comment that all such calculations were mainly theoretical it might be noted that not a single chemical formula was quoted—the whole system being merely simple arithmetic applied with ordinary common sense. It was, therefore, well within the grasp of workmen, sample passers, and students; but should be of most use to others, from shop managers upwards, who had to deal with new works or extensions, choice of process, change of practice, etc., and to everyone concerned in costs—current or prospective. Such matters involved a knowledge of local prices and supply conditions; and every case had to be worked out separately and settled on its merits—which could hardly be done without a reliable system of calculation. In conclusion he wished to apologise for the deficiencies of the paper. There were many points which could not adequately be treated in such a brief review, but he ventured the opinion that the more it was read the more there would be found in it.

In reply to Mr. Talbot as to the advantage of blowing the slag off a fixed furnace he (Mr. Bagley) had always held that the chief advantage of the tilting furnace was the facility of timely removal of the excess slag inseparable from the liquid metal basic O.H. process. For cheap steel ingots on the large scale, that process was essential. Cheap pig iron, usually more or less phosphoric, must always be the basis; hæmatite irons suitable for the acid process were too expensive, while steel scrap was almost worth hæmatite price, and could never be available in sufficient quantity (except locally) on a large scale. With a large proportion of pig iron, even of good quality, a large make of slag was inevitable, which meant small outputs and high costs unless it were readily removable. The various ways of evading that difficulty had already been considered, but the only direct methods of removing the slag without transferring the metal also, were by blowing it off or by the use of tilting furnaces—which, of course, were much more expensive than fixed furnaces of equal size. The extra cost was repeated with every furnace built, whereas the cost of a blowing plant suitable for any number of furnaces was less than the difference between a single tilting furnace and a fixed one of equal size.

The process could also be applied quickly and effectively to existing fixed furnace plants, thus bringing them right up to date instead of scrapping them.

THE ACID HEARTH AND SLAG.

By J. H. WHITELEY and A. F. HALLIMOND, M.A.
(Stockton-on-Tees).

The present paper is a record of observations and experiments made upon the acid open-hearth process during the past few years. The first part consists chiefly of a description of the structure of slowly cooled acid slags and of the stability-relations of the minerals formed in them. This was a necessary preliminary to the study of the structure of the hearth itself, which forms the subject of Part II. Part III. deals with the reactions which occur in the molten slag; it is for the most part independent of the earlier portion and might be read separately. The view is here advanced that an important part of the oxidation of the metalloids is due to the reduction of ferric oxide, which is continually being formed in the slag by the action of the furnace gases. The subject is somewhat controversial, and the authors hope that, though their conclusions may not be entirely in accordance with the views of other workers, the consideration of the reactions from this standpoint may stimulate investigation of the many difficult problems connected with the acid process.

PART I.

The Microstructure and Mineral Composition of Acid Slags.

Most of the acid open-hearth slags described in this paper consist principally of the three oxides FeO, MnO, and SiO_2; they are relatively free from other oxides, such as CaO and MgO, and their behaviour is essentially that of the ternary system FeO–MnO–SiO_2. The slags obtained in the acid processes, while not sufficiently varied for the complete description of this system, serve to define fairly closely the behaviour of the more siliceous melts.

A general discussion of the crystalline constitution of a great variety of slags was published in 1903 by J. H. L. Vogt in his classical work dealing with the application of the principles of physical chemistry to the silicate melts.[1] The majority of Vogt's slags contain important amounts of lime, alumina, or magnesia, and are therefore not of service in the study of the above system. A certain number, however, resemble in composition those here described and have therefore been included in Table I., where a summary is given of the analyses of all the slags of which the microstructures are described in the present paper.

Rate of Cooling.—In dealing with silicate melts the greatest importance attaches to the rate at which the sample is cooled; small samples which have cooled rapidly are most frequently glassy, and even if crystallisation has occurred the conditions may differ widely from those in which the phase rule can be applied. It is important, therefore, to choose for examination samples which have cooled at the slowest rate possible. In the present case samples were taken from slag-balls weighing from 6 to 8 tons, and which had been cooled in air in the usual way. Even here the microstructure shows evidence of a certain degree of super-cooling; the cristobalite in particular is invariably dendritic, a structure which probably indicates that the melt was approaching a labile condition with respect to this substance at the time when it crystallised. These melts may be said, therefore, to be on the border-line beyond which more quickly cooled slags will show increasing deviation from the conditions represented in a "phase-rule" diagram of the usual kind. The effects of super-cooling on the microstructure have been discussed in detail by Vogt, who found that even in cases where the failure of a crystalline substance to appear (owing to super-cooling) gave rise to a deviation from the correct proportions required for the various silicates by the equilibrium diagram, yet the boundaries of the different areas could be ascertained with considerable precision by observing the order of separation of the minerals. The method has been frequently used by other workers on the silicate melts, and by it the diagram given in Fig. 1 has been constructed.

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[1] J. H. L. Vogt, "Die Silikatschmelzlosungen," 1903.

TABLE I.

No.	SiO_2.	Al_2O_3.	Fe_2O_3.	FeO.	MnO.	CaO.	MgO.	TiO_2.	Total.	$\frac{FeO}{FeO + MnO}$	Minerals in Order of Crystallisation.
										Per Cent.	
1	51·2	0·95	1·14	32·91	10·3	1·6	0·44	0·62	99·16	76·1	Tridymite with cristobalite, fayalite, glass.
2	50·5	0·75	1·36	33·55	10·75	1·7	1·05	0·57	100·23	75·7	Cristobalite, fayalite, glass.
3	55·2	1·25	0·70	30·1	9·8	1·9	0·32	0·15	99·42	75·4	Cristobalite with tridymite, fayalite, glass.
4	49·5	2·15	1·13	29·3	14·05	1·8	1·22	0·72	99·87	67·6	Cristobalite with tridymite, rhodonite, glass.
5	49·6	1·90	0·57	27·8	13·4	5·1	0·94	0·64	99·95	67·4	Cristobalite, rhodonite, glass.
6	52·0	1·18	0·57	24·43	13·10	5·8	1·87	0·70	99·65	65·1	Cristobalite, rhodonite, glass.
7	45·2	1·8	0·40	33·2	12·5	4·6	1·6	0·26	99·56	72·6	Rhodonite, fayalite, glass.
8	47·9	1·72	1·2	20·85	10·8	13·0	3·89	0·58	99·94	...	Metasilicate (p. 205), glass with metasilicate.
9	48·2	1·93	1·12	26·0	13·2	7·8	1·37	0·48	100·10	...	Cristobalite, metasilicate, fayalite, glass.
10	56·4	1·45	...	27·6	8·3	5·1	0·91	0·45	100·21	76·8	Cristobalite with tridymite, fayalite, glass.
11	58·1	...	...	23·5	8·4	6·7	0·86	...	...	73·8	Tridymite, rhodonite and cristobalite, glass.
	Minerals separated from the above Slags 6, 7, and 8.										
6*a*	47·0	trace	0·40	29·03	16·6	5·6	1·94	0·05	100·62	63·6	Iron-rhodonite. (Fe, Mn, Ca) O, SiO_2.
7*a*	...	...	...	35·0	14·5	...	...	...	...	70·7	" " " "
8*a*	47·4	0·15	2·7	15·95	12·95	15·1	5·26	0·10	99·61	...	Metasilicate (probably new); separated by roasting, which has increased the Fe_2O_3.
	Slags described by Vogt.										
57	53·9	1·71	...	19·93	21·69	1·86	...	...	99·09	47·8	" Rhodonite slag."
58	47·34	3·52	...	9·06	39·42	0·45	0·03	...	99·82	18·7	" Rhodonite slag."
59	45·61	2·58	...	27·93	17·07	2·41	4·65	...	100·25	62·1	Rhodonite, glass.
60*a*	44·72	2·45	...	28	25	1·89	...	...	...	52·7	Rhodonite, fayalite and rhodonite, glass.
60*b*	42·85	3·94	...	15·62	36·83	0·70	trace	...	99·96	29·7	Rhodonite, fayalite, glass.
61	41·23	2·29	...	22	37	1·19	"	...	...	37·3	Fayalite, rhodonite, glass.

It has been remarked that the acid slags here described are essentially melts of the three oxides FeO, MnO, and SiO_2. In the triangular diagram (Fig. 1, p. 210) the composition of each slag has been represented by a point the distance of which from any one of the three sides is proportional to the percentage of the oxide named at the corner opposite that side. Before the general character of the diagram is considered, it will be necessary to describe briefly the minerals present in the various slags examined and their microstructure. Besides the examination of thin sections by transmitted light according to the usual petrographical method, useful information can often be obtained from the appearance of polished sections under vertical illumination. The latter method has recently been employed by Dr. McCance in a study of the non-metallic inclusions in steel,[1] and is particularly useful in dealing with very fine structures, since the highest magnification can be employed without that loss of definition which occurs with transparent sections, owing to their thickness; the outline of crystals is that of a true plane section, a fact which renders their identification more easy, though, on the other hand, very small fibres and grains appear only as minute points where they meet the surface and are liable to be overlooked.

MINERALS OCCURRING IN ACID SLAGS.

1. *Silica.*[2]—Both the high temperature forms of this substance, namely, tridymite and cristobalite, commonly occur in acid slags, and may often be seen together in one microsection. They are distinguished by means of a slight difference between their refractive indices, and can often also be identified by their very characteristic crystal habits; an account of the methods used has recently been given by Dr. H. H. Thomas,[3] and the minerals here described have been determined in this way.

(*a*) *Cristobalite.*—Even in the largest slag-balls the crystals are dendritic. They occur as skeletal octahedra or, more often, as plates which in section show a curious ladder-like structure, very characteristic of this mineral; these plates are formed through the extension of a crystal by dendritic growth in directions parallel with one of the octahedron faces, usually in the direction of the three edges (Photo. 21). The flat dendrites so produced become covered on either side by a thin continuous film of cristobalite which entraps the interstitial iron silicate of the dendrites. Both the octahedra and the dendritic form are seen in section in Photo. 14. Photo. 26 shows the hollow octahedra in parallel growth on a flat plate from a cavity in the centre of the same slag-ball.

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[1] *Journal of the Iron and Steel Institute*, 1918, No. I. pp. 239–286.

[2] A summary of some recent papers on silica has been given in *Engineering*, December 6, 1918.

[3] *Journal of the Iron and Steel Institute*, 1918, No. II. p. 104.

(*b*) *Tridymite.*—At the temperature of freezing of these slags this is the stable form of silica. It occurs as thin hexagonal plates, which appear as laths in the section (Photo. 1). This habit was very constant in all the slags examined, but in the sections of the furnace-hearth elongated crystals are found, while it may be remarked that in certain silica bricks heated at lower temperatures the predominant habit is an arrow-head twin.

At temperatures approaching the melting point of pure silica, cristobalite is the stable form.[1] This view has recently been questioned by Professor Le Chatelier,[2] but is very strongly confirmed by the evidence here given, for it is found that in the surface layers of the silica bricks, the banks, and the hearth of the acid furnace the silica is present as cristobalite. As regards the banks, at least, there can be little doubt that the material for the most part is in the solid state, even at the temperature of the furnace.

In view of the close similarity between the physical constants of the two forms of silica, it is not surprising to find that they differ but little in stability with respect to the melt, and that both minerals frequently occur together in the same slag in proportions that vary quite irregularly from point to point in the section. As has been said, cristobalite is invariably skeletal, while the tridymite crystals exhibit a stable tabular habit. It seems clear that, on super-cooling, the unstable phase often crystallises first and undergoes rapid growth in the dendritic form. Crystals of tridymite, on the other hand, even when present in a super-cooled melt, seem to have a much slower rate of crystal growth than cristobalite, and are frequently to be seen scattered among cristobalite of subsequent growth.

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[1] *American Journal of Science*, 4th series, 1913, vol. xxxvi. p. 331.
[2] *Bulletin de la Société de Minéralogie*, vol. xl. p. 44.

2. *Silicates of the Olivine Group.*—The orthosilicate (monosilicate) of iron, $2FeO,SiO_2$, which crystallises in this group, is known as fayalite, while tephroite is the corresponding isomorphous manganese silicate. In dealing with such compounds as these, which can crystallise together in a more or less complete series of mixed crystals, the mineral names are generally used to denote also crystals that approximate in composition to the pure compounds. When both bases are present in nearly equal proportions, an ambiguity arises; this is the case with the present group, the iron-manganese olivines from the acid slags are sometimes richer in fayalite, sometimes in tephroite, and both names have been employed by previous writers. Vogt for brevity calls the mineral fayalite, and it will be convenient in the present paper to use this name to indicate all the iron-manganese olivines met with, as well as the pure iron compound.

A mineral containing equal amounts of the fayalite and tephroite molecules has been termed "knebelite." This may be only an intermediate member of the isomorphous series, or it may be a double salt; for the present the name has not been used on account of this uncertainty. The whole olivine group requires a more detailed examination before the true nature of the intermediate mixtures can be ascertained.

These olivines are distinguished by their straight extinction, moderately good cleavage, and symmetrical outlines in thin section. They have a high refractive index, and are generally somewhat brown in the microsection, but are not markedly pleochroic. In slags that have been rapidly cooled the mineral forms very characteristic groups of parallel or radiating crystals.

3. *Silicates of the Rhodonite Group.*—The pure manganese metasilicate (bisilicate), MnO,SiO_2, is one of the end members of a series of mixed crystals which may contain very considerable amounts of the corresponding iron and calcium silicates. The latter must be supposed to be present as the isomorphous compounds, though these have not so far been obtained in the pure state by direct crystallisation from fusion.

The analysis of the rhodonite from slag 6 is given in Table I., 6*a*. In the present investigation it was found that the limit beyond which the slags yielded fayalite instead of rhodonite was reached when the slag contained a ratio $FeO : MnO = 73 : 27$

(p. 210). The rhodonite richest in iron is therefore to be expected from a slag approaching this composition; analysis 7*a* (Table I.) shows the iron and manganese oxides in the rhodonite from slag No. 7, which contained approximately the above ratio, and it will be seen that the ratio of iron oxide to manganese oxide in the mineral has reached the value 71 : 29.

The amounts of lime, manganese, and iron in these minerals are remarkably close to those in the fluid slags from which they separate. How far the amount of calcium silicate in the mineral can increase is not at present known, but it seems likely that the limit is fairly low, for slag 9, which contained 7·8 per cent. of lime, yielded another silicate which will be described below.

The rhodonites are easily recognised by their very well-marked cleavage in three directions, of which two are parallel with the elongation of the crystals and one is inclined obliquely; by their high extinction angle, and by the oblique termination of the crystals. The cleavage causes the rhodonite slags to be rather friable. The refractive index is high and the mineral is usually somewhat brown in thin section, but not markedly pleochroic. Typical rhodonite crystals are seen in Photos. 8 and 24.

4. *Anorthic Metasilicate of Iron, Calcium, Manganese, and Magnesium.*—Slags that are fairly rich in lime yield a mineral which possesses two cleavages parallel with the elongation, but has little or no cross cleavage; when crushed the mineral forms hard needle-like flakes that readily penetrate the skin. The extinction is nearly, but not quite, straight, and the birefringence of the flakes is noticeably low, an optic axis emerging in a direction nearly normal to each of the cleavages. In thin section the mineral is identified by the absence of cross cleavage, by the oblique terminations, and by the low birefringence and low extinction-angle of the longer sections.

The analysis of crystals separated from slag No. 8 (see Photo. 23) is given in Table I., 8*a*. The mineral evidently contains lime as an essential constituent; it is a metasilicate, but its properties do not seem to agree with those of any of the known minerals of similar composition.[1]

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[1] A description of this substance has been communicated to the Mineralogical Society, at the meeting on March 18, 1919; a mineral apparently identical with this in a piece of slag of unknown origin has been discribed by C. Hlawatsch in 1907 and was named by him Vogtite in honour of J. H. L. Vogt.

DESCRIPTION OF THE MICROSTRUCTURE OF THE SLAGS IN TABLE I.

The reference numbers are those of the analyses in Table I., and the sections described are, unless otherwise indicated, from the pieces analysed.[1] It is of some interest to compare the appearance of the transparent section with that of the polished slag under vertical illumination, and a few typical examples have been treated by both methods.

No. 1 (Photo. 1).—The free silica is mainly present as tridymite, in plates which have a lath-shaped section. Among these are a few rounded crystals of cristobalite. The ground-mass is fayalite, which has idiomorphic outlines against small patches of residual brown glass. The silica of the eutectic residue (fayalite-silica) has largely been precipitated on the numerous flakes of tridymite already present; in one portion of the slide, however, the section passed through a crack in the slag into which this residue had drained, and here the silica had crystallised in a second (eutectic) generation, apparently a little later than the accompanying fayalite which forms about four-fifths of the eutectic (Photo. 5) [E 11890].

No. 1. *Polished Section* (Photo. 2).—The tridymite is dark, while the glass is lighter in tone and somewhat mottled, owing to the presence of crystallites. The light constituent is the fayalite, its outlines against the glass often exhibit the symmetry of the olivine group. The glass contains a few small bright crystals of magnetite.

No. 2.—This analysis is very nearly the same as No. 1, but the structure suggests more rapid cooling. Cristobalite is the first mineral to freeze, in extensive dendritic growths which are imbedded in a fine-grained ground-mass of fayalite with a little brown glass [E 11898].

No. 3 (Photo. 14).—Sample taken from the centre of a slag-ball. The free silica is present as large dendrites of cristobalite (p. 202) imbedded in a ground-mass of fayalite and glass. In the larger patches of ground-mass the second (eutectic) generation of silica has crystallised in small grains between the fayalite crystals [E 11901].

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[1] Duplicates of many of these slags have been presented to H.M. Geological Survey the numbers preceded by the letter E refer to registered sections in the Survey collection. The authors desire to express their thanks to the Director for permission to figure slide E 11897 (Photo. 24). The other photographs are from sections prepared by Mr. J. Lomax.

No. 4 (Photo. 3).—Cristobalite (with some tridymite), in scattered plates that show the typical ladder-like section, has been followed by rhodonite in obliquely terminated anorthic crystals that are imbedded in a considerable amount of brown glass [E 11892].

No. 4. *Polished Section* (Photo. 4).—Tridymite, dark; the glass, which is intermediate in tone, contains skeletal octahedra of magnetite; half-tone, rhodonite.

A section taken from the quickly cooled layer, about 3 inches from the outside of the slag-ball, shows that the silica has there been precipitated in numerous small rosettes which occur imbedded in the other constituents (Photo. 15) [E 11891].

Nos. 5 and 6.—The structure in these sections is very similar to that of No. 4.

No. 7 (Photo. 24).—This slag is of unusually low acidity and contains no free silica; the large crystals of rhodonite which form the bulk of the slag are separated by a brown glass in which can be seen narrow elongated crystals of fayalite. The structure is very similar to that of one of the slags figured by Vogt (No. 60*a*), which differs chiefly in containing a lower ratio of iron to manganese [E 11897].

No. 7. *Polished Section* (Photo. 12).—The edges of large rhodonite crystals are partly seen at each side of the photograph. In the centre is an area of glass containing small rhodonite crystals. Two crystals of fayalite, of a paler tint than the rhodonite, are imbedded in the glass; one has symmetrical outlines, the other is partially included in one of the large rhodonite crystals.

No. 8 (Photo. 23).—This slag is of rather low acidity and contains no free silica. The anorthic metasilicate described on p. 205 is the principal mineral and occurs in flat elongated crystals, which sometimes attain a length of several inches and are often hollow, the interior being filled with glass. The interstitial glass contains many small curved crystals of the same mineral. The analysis of the separated silicate is given in Table I., 8*a* [E 11896].

No. 9 (Photo. 7).—Plates of cristobalite with the usual ladder-like section have been partially enveloped by elongated crystals of the anorthic metasilicate;[1] the interstices are filled with a brown glass in which are narrow lines of fayalite. The structure of the glass is really complex, as will be seen in Photo. 8, which shows a polished section of the same slag. The dark irregular grains are part of one of the large plates of dendritic cristobalite, while the metasilicate is seen on the opposite side as a sharply angular crystal, and the intervening space represents one of the dark areas in the transparent section. This last portion is composed almost entirely of small crystals; one of the bands of fayalite is visible as a series of crystals, in parallel orientation, which appear much brighter than the metasilicate; the remaining space is occupied by a dark constituent, which may still be glassy and which contains thin curved metasilicate crystals that are in places evidently continuous with the larger crystal of the same mineral.

Nos. 10 and 11.—The specimens and microsections used for the following description were kindly transmitted by Mr. Allan B. Dick, to whom the authors desire to express their thanks.

The slag was made many years ago in a Siemens furnace in Scotland; it was collected and preserved on account of the presence in it of remarkable spherical nodules, which measured from half an inch to 2 inches in diameter. When the slag was broken the nodules readily became detached from the matrix through the presence of a porous layer at the surface of the spheres; when split open they showed a crystalline fracture radiating from the centre. Microsections show that the matrix (Photo. 25) is a typical acid slag containing plates of dendritic cristobalite in a ground-mass of fayalite and glass; the nodules (Photo. 6) contain scattered flakes of tridymite, together with a certain amount of cristobalite, in small rounded grains, but the ground-mass is rhodonite, which has a radiated structure; this, too, is the normal structure of a certain class of acid slags and resembles Nos. 4, 5, and 6. As will be shown later, the acid slags may be grouped according to the silicate present, the formation of fayalite or rhodonite being conditioned by the ratio of iron to manganese in the liquid slag. The analyses of the slag matrix (No. 10) and of one of the nodules (No. 11) are given in Table I.; these analyses lie very close to the critical analysis separating the two classes (*cf.* Fig. 1).

When a slag of this composition has become super-cooled both structures are possible, and the nature of the silicate which crystallises may be determined by accidental causes, such as the introduction of suitable nuclei. In the present instance it would appear that, when the mass was super-cooled with respect to silica and rhodonite, crystallisation of rhodonite was initiated at a few centres, from which grew spheres of rhodonite slag in which the free silica was deposited as small grains that are often enclosed within the rhodonite crystals. The acid slags contain a certain amount of gas, and the liberation of this from the slag as it crystallised will no doubt account for the porosity at the surface of the nodules. When the spheres had grown to a certain size, the surrounding liquid, which had meanwhile deposited large dendritic plates of cristobalite, solidified with the formation of fayalite, so that the nodules of rhodonite slag were enclosed in a normal fayalite slag.

THE TERNARY DIAGRAM, FeO–MnO–SiO_2.

The triangular diagram represented in Fig. 1 has been constructed from the analyses of the slags described in the preceding section. The points shown represent the composition of the slags as given in Table I., the number placed near each point being that of the sample in the table. Owing to the presence of small amounts of other substances, the total percentage of the three oxides is always somewhat below 100, and it was therefore necessary to adopt a fixed order in plotting the values; the method used was to divide the base of the triangle in the ratio of the iron and manganese oxides present and to mark off the representative point upon the line joining the apex to this division of the base, at a value corresponding with the percentage of silica present. The diagram thus obtained can be regarded as approximately that of the ternary system, but it must necessarily remain incomplete until a full determination of the system has been made by the experimental preparation of those melts which are not encountered among the acid slags; for the present it may serve as a guide for the study of the materials of the acid process.

In accordance with the usual practice, the diagram has been divided into areas; each area includes the compositions of those melts from which one of the minerals concerned is the first to separate on cooling. In most of the slags analysed silica was the first mineral to freeze, the slags being generally more acid than those described by Vogt. The silica was followed by a silicate, and it was soon observed that the slags could be divided into two groups, in one of which the silica was followed by rhodonite, in the other, by fayalite. The factor determining which silicate shall form is the ratio between the FeO and MnO in the slag, the two classes being separated by the critical ratio FeO : MnO = 73 : 27; with more manganese, rhodonite is obtained; with more iron, fayalite. When the slag deposits free silica its composition changes during the separation of the silica along a line which is the continuation of that joining the apex

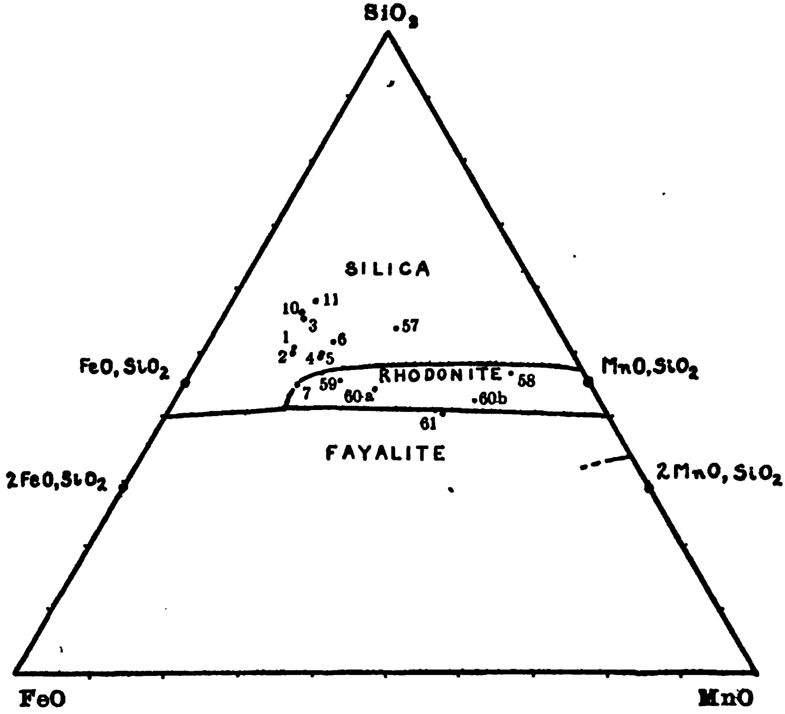

FIG. 1.—The Ternary System FeO-MnO-SiO_2.

SiO_2 with the representative point of the slag; when the liquid has attained the composition of the eutectic, in the absence of super-cooling, the silicate and silica separate together in the eutectic proportion.

The binary system, SiO_2–MnO, has been described by Doerinckel, whose diagram has recently been reproduced by McCance.[1] The points in Fig. 1, on the line SiO_2–MnO, have been taken from these data. In the binary diagram the silica-line meets the rhodonite-line practically at the melting point of rhodonite. There is thus no eutectic between the two compounds, the separation of silica being followed by that of the rhodonite. From the structures previously described it is clear that, in the ternary diagram of Fig. 1, the boundary between the silica and rhodonite areas must pass between slags 4 and 5, and slags 7 and 59. The proportion of free silica in the fayalite slags is greater than that in those yielding rhodonite, and the boundary must therefore turn sharply downwards as it approaches the ratio $FeO : MnO = 73 : 27$. Beyond this ratio fayalite separates, and at this point, therefore, the three boundaries between fayalite, silica, and rhodonite must meet.

The boundary fayalite-silica represents a well-defined eutectic. A true eutectic structure is sometimes to be observed in the mill cinders (soaking-pit cinders), where, as far as can be judged from microsections, the eutectic contains about 40 per cent. total silica and 60 per cent. FeO. The boundary is probably fairly horizontal between this and the ternary eutectic point. The eutectic structure is not well seen in the slowly cooled slags, but in slag No. 3 (Photo. 14) the ground-mass consists of an aggregate of silica and fayalite in about the eutectic proportion. In slag No. 1 the section had passed through a vein of similar eutectic material that had flowed into a crack during the solidification; this is seen in Photo. 5.

Like the preceding boundary, that between rhodonite and fayalite appears to be nearly horizontal; it passes between Vogt's slags 60*b* and 61, and meets the side of the diagram at $MnO = 60$ per cent.

Tephroite is stated to be unstable at its melting point, and the boundary between tephroite and MnO starts from

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[1] *Journal of the Iron and Steel Institute*, 1918, No. I. p. 246.

SiO_2 = 32 per cent. Concerning the further course of this boundary and the behaviour of the less siliceous melts no information is obtainable from the slags here under discussion.

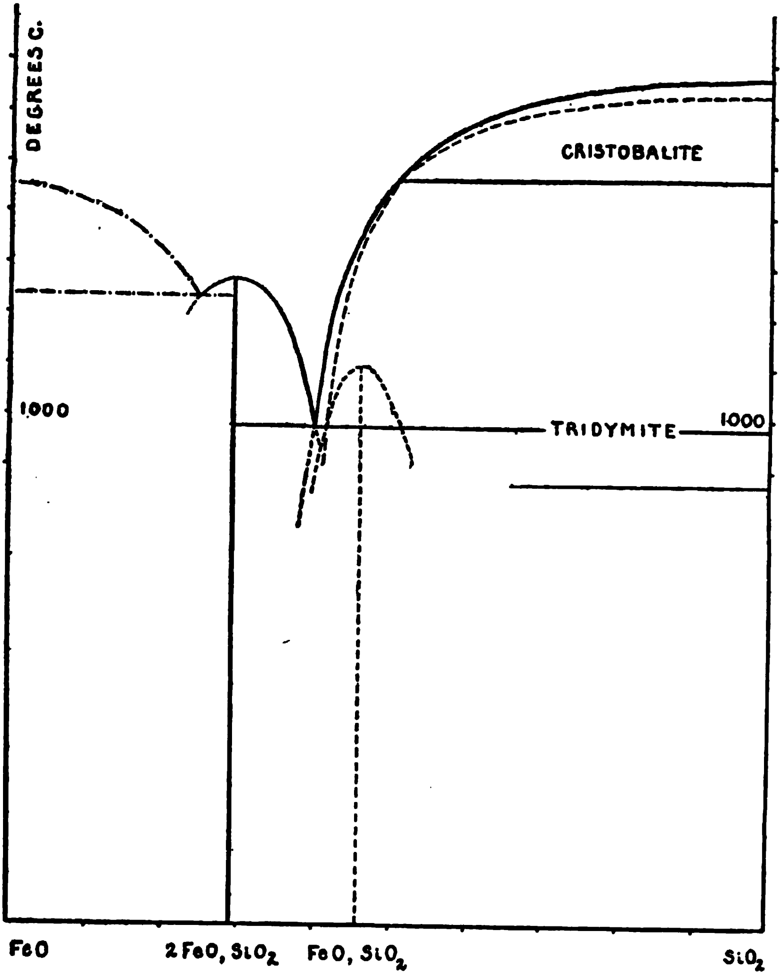

FIG. 2.—Approximate Diagram of Binary System FeO–SiO_2.

In concluding this account of the ternary diagram, it may perhaps be remarked that the similarity between the systems FeO–SiO_2 and MnO–SiO_2 is very strongly marked. It is true that the metasilicate of iron does not appear, but this does not imply any great difference in stability between the two metasilicates; the rhodonite surface evidently passes beneath that of silica by a gentle inclination, which suggests that the stability line or melting-point curve of the iron member of the rhodonite group is only slightly below that of silica. This may be represented in the manner shown in Fig. 2.

SLAGS CONTAINING LIME.

Small amounts of lime are present in many of the analyses already discussed. The corresponding silicates of lime are soluble isomorphously in both rhodonite and fayalite, and their presence does not at first greatly disturb the equilibrium relations. With large amounts of lime (over 8 per cent.) another mineral is formed which, like rhodonite, is a metasilicate containing manganese, calcium, and iron (p. 205). The long crystals have a brilliant cleavage, and in slags of which the composition approaches that of the pure silicate the mineral is the cause of great inconvenience when the slag is crushed for road-metal. Vogt examined many lime slags, but these were in general richer in alumina or magnesia; the minerals observed include augite and olivine, but the present silicate does not seem to have been encountered.

For those slags which yield free silica, the nature of the silicate will be determined by the ratio of the three bases FeO, MnO, CaO; these could conveniently be represented in a triangular diagram, but many more analyses will be required before even this section of the quaternary system can be described with sufficient accuracy.

THE STRUCTURE OF REHEATED ACID SLAGS.

In order to examine the growth of tridymite at temperatures somewhat above the eutectic point, but below that at which the inversion to cristobalite occurs, two specimens of slag of similar composition, in the glassy and crystalline states respectively, were enclosed in a steel cylinder and heated for eighteen hours at a temperature of approximately 1300° C. The case was withdrawn from the furnace and cooled in air;

when the pieces were removed it was found that they had retained their shape, but had become welded together. The structure of the reheated glassy slag (part of a spoon sample) is shown in Photo. 10; it consists of plates of tridymite in a glass that is stained by a slight oxidation. The crystalline sample (slag No. 1, Photo. 1) is shown in Photo. 11; the plates of tridymite originally present have been partially redissolved by the melted fayalite, and remain imbedded in a brown glass. It is clear from this experiment that tridymite is really stable in contact with the melt at 1300° C. The structures botained resemble those found in the acid hearth.

THE STRUCTURE OF QUICKLY COOLED SLAG SAMPLES.

In the small "spoon samples" (2 to 3 inches in diameter) which are withdrawn from the slag during the process, a very interesting structure is to be observed; it is probably the same as that referred to by McCance,[1] and consists of very minute crystals or crystalline rosettes imbedded in a glassy matrix. Under vertical illumination the crystals appear dark grey in contrast with the lighter background (Photo. 13); this tint is similar to that always given by the crystalline forms of silica. In transmitted light the particles in thin sections are seen to be transparent and colourless; their refractive index is much lower than that of the glass in which they occur, and also in crushed material was found to be lower than 1·55. It is thus fairly certain that they are a form of silica; this was confirmed by digesting the slag in dilute hydrochloric acid, when the particles were left as a fine white powder which volatilised with hydrofluoric acid. The mineral has been mentioned by Vogt, who observed it in very acid slags, and surmised that, if a silicate, it contained a very high percentage of silica; he termed it the "enamel-mineral," on account of the dull lustre which it imparts to the slag.

The particles are common in acid spoon samples, and can appear even in quickly cooled melts which would normally yield fayalite. They are sometimes to be observed in the crystalline slags where super-cooling has occurred; thus the exterior of the slag-ball which yielded analysis No. 4, at a distance of 3 inches from the surface, contained rather large rosettes imbedded in the other constituents (Photo. 15). As Le Chatelier has remarked, glasses generally devitrify with the formation of cristobalite, so that it is most probable that the particles are this mineral and not tridymite.

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[1] *Loc. cit.*, p. 266.

As soon as a spoonful of slag is withdrawn from the bath, the furnace gases, and, later, the air, begin to oxidise the upper layer. When the cold sample is fractured, the surface is seen to be tinted a deep brown or black to a depth which varies with the character of the slag, and may extend to a distance of $\frac{3}{16}$th of an inch; this action takes place chiefly before the slag is set, for samples which have been covered with carbon immediately on withdrawal from the furnace still show an oxidised layer. A section through a typical spoon sample of a slag comparatively free from lime is shown in Photo. 9. Even in the thin section (about $\frac{1}{500}$th inch) the slag is rather opaque, and the structure is best revealed by oblique illumination, which was used in taking the photograph. The pale glassy centre of the sample is seen in the lower part, and above it is the dark oxidised layer in which are several gas bubbles. It is a curious fact that the limit of the crystallisation which extends from the surface downwards is marked by the lower dark boundary; in other cases the deep-brown colour extended beyond the crystallisation.

Some idea of the extent of the oxidation may be obtained from the following analyses of the various layers in one of these spoon samples:

	FeO.	Fe_2O_3.
	Per Cent.	Per Cent.
Top layer	28·9	2·71
Middle layer	30·2	1·3
Bottom layer	30·1	1·42

It will be understood that in testing spoon samples for Fe_2O_3 the top layer must always be rejected.

In Part III. of this paper the view will be advanced that gas oxidation takes place partly through the absorption of oxygen by the upper layers of the slag. The depth of the oxidised skin in the spoon sample affords a useful indication of the power of the slag to absorb oxygen. Thick slags invariably show less penetration than thin slags, as is well seen in samples taken before and after an ore addition. Again, limey slags generally have a thin oxidised layer, and it will be shown later that such slags retard the gas-oxidation of the charge.

PART II.

THE ACID HEARTH.

Although the acid hearths which have been examined during the course of the present investigation were originally made of silica stone and sands containing over 96·0 per cent. of silica, yet the analyses of these hearths, taken after they had been in use for considerable periods, invariably showed a much lower silica content, and micro-sections through different parts revealed the presence of large quantities of slag. The analyses of pieces from various positions in three old hearths are given below:

TABLE II.

	1.	2.	3.
	Per Cent.	Per Cent.	Per Cent.
SiO_2	67·00	67·20	68·10
Fe_2O_3	7·70	0·30	0·90
FeO	22·90	19·80	23·10
MnO	1·10	6·60	3·90
Al_2O_3	0·28	2·80	2·10
CaO	0·50	2·20	1·10
MgO	0·05	0·04	0·15
TiO_2.	0·03	1·20	...
	99·56	100·14	99·35

No. 1, taken a few inches beneath the surface at a point about 2 feet below the wash (Photos. 18 and 19). No. 2, taken near the limit of penetration of slag in the bricks beneath the crushed ganister used in making the lower part of the hearth. No. 3, taken just above the top layer of bricks (Photo. 20).

The above analyses may be regarded as representative of the composition of acid hearths which have been in use for some weeks and where lime has not been added in any great quantity to the slags.

Microstructure.—Photos. 16, 18, 19, and 20 illustrate the microstructure of various parts of the acid hearth.

Photo. 16.—Bank, near surface exposed to the gas, showing a patch of slag rich in dendritic crystals of magnetite, between which are lighter areas of fayalite and a few plates of tridymite. The white ground-mass is entirely cristobalite and contains smaller slag inclusions. Very little trace of the structure of the original sand grains is to be seen. The presence of the magnetite is no doubt due to the oxidation of the surface layers during the cooling of the furnace [E 11708].

Photo. 18.—Old bottom (analysis No. 1). Interlacing needles of tridymite in fayalite with areas of brown glass. The position of the original sand grains can still be seen [E 11537].

Photo. 19.—Another part of the same section; cristobalite and tridymite areas in juxtaposition.

Photo. 20.—Lower part of the hearth near the brickwork (analysis No. 3). Grains of quartz sand and ganister, superficially converted to tridymite, in brown glass containing fayalite crystals.

These and similar sections show that the hearth in use consists of a mass of interlacing crystals of tridymite, the interstices of which are filled with slag. For a small distance below the surface the temperature is sufficiently high to cause the formation of cristobalite in place of tridymite. Numerous analyses showed that the proportion of slag is remarkably constant throughout the whole mass down to the limit of penetration, which usually lies in the upper courses of the brickwork. The silica content throughout is generally from 67 to 70 per cent. During the working of a charge, the average temperature of the hearth will be above that of the melting point of the interstitial slag; this will therefore be fluid and in equilibrium with the excess silica. The amount of undissolved silica at any point will depend upon the temperature and the quantity of slag present. The upper surface of the hearth will be at the temperature of the molten metal while, at the limit of slag penetration, the temperature will scarcely exceed 1000° C.; there is thus a wide temperature variation through the hearth, and the proportion of undissolved silica will consequently decrease towards the upper surface.

Complete fluxing of the hearth in contact with the molten metal is prevented by the additions of quartz sand made in "fettling" the bottom after the charge has been tapped. Toward the end of the process the temperature of the upper layer is not far removed from the melting point of pure silica, and it might be expected that the large amount of impurities present in the hearth (about 30 per cent.) would lower the melting point to such a degree as would bring about complete fusion. The depression of the freezing point of silica by impurities seems, however, to be exceptionally small; the point of complete fusion of a mixture containing as much as 50 per cent. of ferrous oxide was found to lie at about 1500° C., and the freezing-point curve must have such a form as that shown in Fig. 2. A similar behaviour of silica has been recorded for other systems.[1] There can be no doubt that this property of silica plays a most important part in maintaining the stability of the acid hearth.

It will be seen from the analyses (Table II.) that the slag present in the hearth resembles generally the ordinary acid slag, such as No. 1, Table I. The ratio of iron to manganese in the hearth is, however, distinctly higher than that in the slag; in accordance with this ratio, the silicate found in the sections is invariably fayalite (*cf.* Fig. 1). A certain amount of metal as well as slag is always left on the bottom after tapping; during the subsequent "fettling" of the hearth this metal will be rapidly oxidised by the flame, and the iron content of the slag will be thereby increased. In order to verify this conclusion, some slag was removed from the hearth just before the sand additions were made and after the banks had been repaired. The iron and manganese contents of this sample and of the finishing slag were then ascertained, the quantities found being as follows:

	FeO. Per Cent.	MnO. Per Cent.
Finishing slag	27·1	13·2
Hearth slag	36·2	4·5

The hearth slag has clearly been enriched with iron oxide, and the ratio of iron oxide to manganese oxide in this residual slag is very similar to that found in the hearth itself.

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[1] *American Journal of Science*, 4th Series, vol. xxxvii. p. 487.

Changes occurring on "Making" and "Fettling" the Hearth.—In view of the comparatively low silica content of the hearth in actual service, it is somewhat surprising that the smelter almost invariably requires a very high degree of purity in the sand used. Even in the case of a sand which would be rejected, owing to a low silica content, the quantity of impurity present may still be quite negligible in comparison with the large amount of slag subsequently taken up. Evidently, in requiring a pure sand, the smelter cannot aim simply at the production of a highly refractory hearth, and the degree of purity necessary in the sand employed must therefore be determined by other factors.

There can be no doubt that a combination of properties is essential in a silica sand which is to be used for making and "fettling" the acid hearth. Among the physical properties the grain size, grading, angularity, and angle of rest must all be considered, and these alone form a combination which it would be almost impossible to define within the limits of any practical specification.[1] Even if a sand is satisfactory in these respects it may still be rendered unsuitable by its chemical composition. In this connection, three indirect ways in which small amounts of impurity will affect the quality of a sand may here be mentioned.

(1) The smelter attaches great importance to the ease with which a sand can be made to lie at a steep angle on the banks.[2] This is, of course, largely a physical property, but the presence of small amounts of impurity on the surface of the grains will cause fritting and so assist in the production of a "hard" steep bank, while a greater proportion of impurity, especially in the case of certain fluxes, such as the alkalies, will rather tend to prevent the cohesion of the grains to form a rigid mass and so cause the sand to be "soft." In this respect alumina does not seem to be as harmful as other common impurities.

2. The rate of inversion of quartz to tridymite is greatly influenced by the presence of impurities; the change causes

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[1] See P. G. H. Boswell, "Refractory Sands," 1918, p. 58.

[2] It is important to observe that the temperature of the sand after being placed upon the banks during fettling may be considerably lower than has sometimes been assumed; the gas is sometimes off for several minutes before fettling is completed, and the cold sand probably does not reach a temperature exceeding 1000° C. before all movement has ceased.

the grains to break up through flawing and crystal growth, with the consequent admission of slag and softening of the mass. Thus it may be said that in general the slower the inversion the better will be the refractory properties of the sand (for temperatures below the melting point of quartz) during the early part of the heat. Since the presence of small amounts of impurity in the mass of the grain has a considerable accelerating action on the change, it is clear that on this account, whatever the composition of the external layer, the interior of the grain, at any rate, should have a very high degree of purity.

8. It would naturally be supposed that the higher the silica content of the hearth the more satisfactory would be its service. Experience, however, indicates that it would be impossible to carry out the process continuously upon a pure silica hearth. The softening action of the fluid slag content is of the greatest value in counteracting the tendency of the hearth to crack while cooling between successive heats. Such cracks when formed are quickly filled with molten slag, or even with metal from the bath, and during the "boil," as the temperature of the hearth increases, the fluid area extends, and may either penetrate the bottom or cause a portion to be detached and so give rise to a "hole."

After the furnace has been tapped a certain quantity of slag and metal is always left on the bottom. As far as possible this is removed by the smelter, but some inevitably remains, especially in the grooves and holes present. An important function of the sand which is added in "fettling" is to absorb this residual slag, so as to produce a uniform layer which replaces the material removed from the hearth during the previous heat. If the sand employed contains any considerable amount of impurity, the interstices of the new layer will become filled with fused material, which will render the whole mass non-porous before the underlying viscous slag has time to penetrate. The slag thus confined beneath the new sand becomes a source of weakness when the temperature of the furnace is again raised, and the whole mass of sand may separate from the hearth and float up to the surface of the bath.

Where a hole in the bottom has been repaired with suitable sand, the silica content of the new part will eventually approximate to that of the hearth in general, owing to the absorption of slag. During the subsequent heat the quartz of the sand undergoes a gradual transformation to tridymite (this was complete in a piece which came up two hours after the boil), but the shape of the sand grains is only slowly obliterated. Each grain becomes surrounded by a fringe of tridymite (Photo. 17), and these fringes grow until the structure has changed to a loosely felted mass of tridymite crystals (Photo. 18), the spaces between which are filled with fluid slag.[1] The stability of the hearth will thus depend on the viscosity of the interstitial slag and on the rigidity of the tridymite network. This structure may be compared with that of plaster of Paris saturated with a liquid which fills the pores between the needles of hydrated calcium sulphate; in such a structure a relatively small proportion of solid matter will suffice for the production of a rigid mass.[2]

A striking instance of the failure of an impure sand that was used for repairing a hole in the hearth may here be mentioned. The sand contained about 5 per cent. of alumina as kaolin, and traces only of other impurities. The whole patch floated up during the "boil," and was found to be pure white in fracture and completely free from included slag. Most of the silica had been transformed to cristobalite, but in places the material was much denser, resembling porcelain, and on sectioning was seen to consist of very closely packed quartz grains surrounded with glass containing sillimanite (Al_2SiO_5) needles. The quartz grains were, in many places, regrown, as shown in Photo. 22, where the outlines of the original sand grains can clearly be seen within the larger crystals that have grown in continuity with them. The deposition of quartz in this way is remarkable; it is probably due to the retention of water from the kaolin, owing to the pressure of a heavy piece of metal resting upon the patch.

The foregoing considerations make it clear that the purity of the sand used for the acid hearth is of great importance. The need for a sand which will not fuse to a solid mass, but will retain its porosity at the temperature of the furnace, demands material of higher purity than would be required if it were merely necessary to provide a refractory lining, and for these reasons alone the silica content must be considerably higher even than that required in a silica brick directly exposed to the flame in the walls or roof of the furnace.

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[1] There can be little doubt that the presence of the absorbed slag in the new sand greatly facilitates the formation of the tridymite crystals.

[2] At the upper surface of the hearth, where cristobalite is present instead of tridymite (Photo. 19), the structure is probably virtually fluid, but this thin layer is doubtless retained in position by its viscosity. In this connection, it is interesting to note that the silica content of the roof-drip was found to be very little lower than that of the hearth.

Presence of Ferric Oxide in the Hearth.—The proportion of ferric oxide in the hearth analyses is lower than the average amount present in the finishing slags. This is the case in spite of the fact that air and gas play upon the hearth after tapping and cause the formation of much ferric oxide at the surface, as shown by analysis No. 1 in Table II. It is clear, therefore, that a reduction of ferric oxide must occur during the subsequent heat, otherwise the percentage in the lower part of the hearth should be much greater. Among the causes contributing to this reduction may be mentioned—(1) The penetration of carbon monoxide, which probably diffuses fairly readily in the silicates at the hearth temperatures. (2) The penetration of metal into the hearth. (3) The decomposition of ferric oxide by silica at high temperatures; this will be further discussed in Part III.

The presence of ferric oxide in the hearth has a certain practical interest, for it is commonly remarked by the smelter that the bottom "works" the metal; this effect is very probably due to the ferric oxide formed in the surface layer after tapping.

The study of the acid hearth raises many questions to which no definite answers can yet be given. The actions of chromium and manganese slags, for example, require examination, for while the former tend to preserve the hearth the latter often cause a rapid corrosion of the surface.[1] Manganiferous metal has at times a similar effect to that of the slag, but here it is necessary to take into account the reducing action of manganese on silica;[2] the replacement of silica by manganese oxide has a double effect in diminishing the acidity of the surface layer of the hearth and a small loss of silica in this layer will suffice to render it dangerously fluid.

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[1] A. McWilliam and W. H. Hatfield, *Journal of the Iron and Steel Institute*, 1904, No. II p. 216.

[2] J. E. Stead, *Proceedings of the Cleveland Institution of Engineers*, 1913–14, p. 195.

PART III.

The Molten Slag.

The durability of the acid hearth is partly dependent on the composition of the molten slag with which the banks are in contact during the process. In the course of work on this subject numerous analyses of the slag at various stages were obtained, and the following pages contain a discussion, based on these experiments, of some of the reactions occurring in the liquid slag. The manner in which the composition of the slag is regulated by the furnaceman is first indicated, and an account is then given of observations on the part played by the slag in the oxidation of the metalloids. Gas-oxidation is an important feature in the process, and was found to be closely connected with the action of ferric oxide as a carrier of oxygen from the gas to the metal.

1. *Regulation of the Acidity of the Slag.*—In judging the condition of the slag in the acid process the smelter is chiefly guided by its viscosity and activity. A slag high in silica will be thick and inactive, while a slag which is too basic will be thin and dangerous to the banks, owing to the readiness with which it will dissolve silica. Up to and during the " boil " the elimination of the metalloids is accompanied by the removal of iron oxide from the slag, so that if the reaction is allowed to proceed for a time without further ore additions the slag gradually thickens, owing to its increasing silica content. The correct viscosity has therefore to be maintained by frequent additions of iron oxide. At first, on account of the rapid thickening action of the metal, large additions may safely be made without damage to the banks, but as the metal begins to drop off the " boil " this thickening action becomes slower, and the furnace must then be fed with smaller or less frequent additions of ore. An excess of iron oxide in the slag at this stage is not rapidly removed, and if too thin a slag is obtained after the metal has dropped off the " boil " serious damage to the banks may result, especially if the temperature is high.

2. *The Use of Lime.*—Like iron oxide, lime thins the slag, its

effect being about equal to that of an equivalent weight of ferrous oxide. If a limey finishing slag is too thin it will attack the banks much as does an iron slag of similar viscosity. When using lime, therefore, the smelter must still be guided by the viscosity of the slag, although perhaps somewhat more latitude in this respect is allowable. In general, it seems to be the practice to work to approximately the same degree of viscosity whether lime is present or not ; and since, at a given temperature, the viscosity is determined chiefly by the silica content, it follows that the sum of the basic oxides present in similar slags of varying composition must be about constant. Seeing that lime is not removed from the slag during the process, as is the case with iron oxide, its use must be accompanied by a lowering of the iron content ; the quantity of lime present in the finishing slag will be the sum of the amounts added, and, as the total bases remain the same, the quantity of iron oxide present will be correspondingly decreased, provided, of course, that sufficient carbon is present to remove it. Lime additions may thus be said to lower "automatically" the iron content of a slag by a process which is quite unconnected with any chemical equilibrium between these bases and silica.

3. *The Removal of Carbon by Gas-Oxidation.*—As is well known, the three principal elements to be removed from the charge by oxidation in the acid process are silicon, manganese, and carbon. Two sources alone are available from which the necessary oxygen can be obtained ; they are first, the ores added in "working" the charge, and second, the oxygen content of the gas which plays continually upon the surface of the bath, for it has already been shown that the hearth itself contains very little available oxygen. By oxidation with ore the yield is increased ; with gas-oxidation it is diminished.

The amount of oxygen obtained from the two sources, either throughout or during any period of the process, can be ascertained with a fair degree of accuracy from the analysis of slag and metal samples taken before and after the addition of a measured amount of ore. From such data it is easy to calculate the weight of the metalloids removed and to compare the amount of ore used with that theoretically required in the absence of gas-oxidation. A table of the "percentage of gas-oxidation" with different charges has been given by Matthewman and Campion,[1] but without the data on which it is based. The following examples will serve to indicate the extent to which gas-oxidation has occurred in two charges—(*a*) Worked in the usual way without any lime additions; (*b*) with lime additions.

(*a*) The charge (100 tons) contained, when melted and just before the first feed of ore was given:

	Per Cent.
Silicon	1·10
Manganese	0·50
Combined carbon	2·20

On tapping, the carbon in the bath had been reduced to 0·10 per cent. This charge was worked with an ore consisting of nearly pure ferric oxide. The oxidation of the silicon produced 2·35 tons of silica, and since the average analysis of the slag throughout the process showed silica 50 per cent. and iron 25 per cent., the oxidised silicon would require 1·7 ton of ferric oxide in forming the additional slag; by this reaction 0·17 ton of oxygen was liberated, for practically all the iron of the acid slag is in the form of ferrous oxide.

The total oxygen required for the removal of the metalloids was silicon, 1·25 ton; manganese, 0·14 ton; carbon, 2·80 tons; making a total of 4·19 tons; of this oxygen 0·17 ton was supplied by the ore (1·7 ton) in forming slag, and the residue 4·02 tons, in the absence of gas-oxidation, would have to be supplied by the reduction of 13 tons of ore, so that in all 14·7 tons of ore would have been consumed. The actual quantity of ore used was only 9·0 tons,[2] and therefore the additional oxygen required for the completion of the reactions must have been derived from the gases.

The removal of silicon and manganese took place rapidly as the metal was brought to the "boil," during which time a large part of the ore used was added. The gas-oxidation, which operates throughout the process, must thus be chiefly concerned in the much slower removal of the carbon, and it may be said that about 5·7 tons of the ore (the amount required by theory) were used to remove the silicon and manganese and to make slag and the remaining 3·3 tons to remove the carbon. If the whole of the carbon had been oxidised by means of the ore 9·3 tons would have been consumed instead of 3·3 tons, and it is clear, therefore, that approximately two-thirds of the carbon was eliminated by gas-oxidation and only one-third by ore additions.

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[1] *Journal of the West of Scotland Iron and Steel Institute*, vol. xx. p. 138.

[2] The weight given is the available Fe_2O_3 content of the ore used; slight corrections necessary, owing to the presence of a little silica in the ore, have been omitted. It is assumed that the carbon, silicon, and manganese were respectively oxidised to CO, SiO_2, and MnO, and that no silica was absorbed from the bottom and banks after melting. If the last action occurred to any extent more ore would be used in forming slag, thus leaving even less oxygen available for the removal of the metalloids.

(*b*) Samples of slag and metal were taken from a furnace when the carbon was about 0·80 per cent. The charge was then worked almost entirely with lime (CaO); as the slag thickened after each addition, more lime was added, until the carbon had fallen to 0·12 per cent. Towards the finish the slag became very inactive, and about 2 cwts. of ore were therefore used. The analyses of slag and metal samples were as follows:

	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Carbon in metal	0·80	0·50	0·20	0·12
Ferrous oxide in slag	35·50	30·0	21·20	21·90
Ferric oxide	0·10	0·10	0·15	0·30
Lime	2·0	...	...	13·6

Weight of charge, 70 tons; slag, 10 tons.

It will be seen that during this period 0·48 ton of carbon was eliminated; this amount would require at least 0·64 ton of oxygen, of which 0·03 ton was obtained from the ore added, and 0·3 ton from the reduction of the FeO in the slag. The remainder, 0·31 ton, must have been derived from the gases, so that, in this instance, about 50 per cent. of the carbon was removed by gas-oxidation.[1]

The amounts of gas-oxidation found in the above examples are similar to those given by Matthewman and Campion. The exact amount occurring in any particular instance will depend, however, upon a number of factors, among which must be included temperature, character of slag, quality of ore used, relative quantities of gas and air employed, and the speed of working.

4. *Physical Conditions which Obtain during the Process.*—Before the chemical reactions involved in gas-oxidation can be considered, it is necessary to examine the physical conditions under which the process is carried out. As soon as the charge is melted the metal becomes covered with a layer of slag, and

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[1] So far as an appreciable amount of oxygen was present in the metal as FeO when lime was first added, and was removed during the period considered, a small reduction in this quantity will be necessary.

from this stage onwards the slag, especially during the boil, is continually traversed by bubbles of CO gas evolved from the metal below. These will saturate the slag with CO, and will effectually prevent the penetration of the furnace gases, which might otherwise reach the lower layers by diffusion or convection and react directly with the metal.

Throughout the process the slag is constantly in contact with both the metal and the gas, and under given conditions its degree of oxidation at any time will depend on the relation between the reducing action of the metal and the oxidising action of the gases.

Beside the slag-metal and slag-gas reactions there is also that which occurs between the metal and the gas; evidence will be given later showing that a considerable amount of gas-oxidation during the " boil " takes place by direct action of the gases on the numerous globules of metal which are continually being thrown up to the surface of the slag.

5. *Reaction between Metal and Slag.*—The oxidation of the metal by the slag may be regarded as purely a surface reaction, the only exception to be considered being the possibility that FeO passes into the metal from the slag and is there reduced by the carbon. The reacting surface, and consequently the speed of oxidation, is subject to wide variations at different stages of the process, owing to the suspension of fine globules of metal in the slag through the ebullition of gas from the bath. The percentage of this suspended metal in spoon samples of slag taken at various periods was determined by removing the globules from the crushed sample with a magnet; the following results are representative of several series obtained in this way:

Period.	Suspended Metal. Per Cent. by Weight.
Melting (very large globules)	12·0
Before boil (small pellets)	0·5
Boiling	5·0
Off the boil, c.c. 0·25 per cent.	0·1
Tapping, c.c. 0·15 per cent.	0·1

These figures show that as soon as the carbon reaction begins the number of metal globules in the slag very greatly increases, and there can be no doubt their presence is due to the agitation caused by the evolution of CO. When it is considered that in, say, a 100-ton charge no less than half a ton of metal is in suspension in the slag during the boil and is constantly being renewed, it is not surprising that the speed of removal of carbon during the boil is considerably greater than that which can be obtained in the finishing stages.

The following analyses of slag globules and metal samples taken simultaneously will suffice to indicate the extent to which the globules lose their carbon content during their short stay in the slag:

Carbon in Metal.	Carbon in Globules.
Per Cent.	Per Cent.
2·11	1·76
1·99	1·72
1·36	1·26
0·80	0·75
0·56	0·56

6. *Reaction between Slag and Gas.*—Like the preceding the oxidation of the slag by the gas is a surface reaction, but in this case the action is very probably aided by the physical solubility of the gases in the uppermost layers of slag. The rate of oxidation will depend on the area of the bath, on the temperature, on the composition of the oxidising gases which play upon the slag, on the amount of FeO in the slag, and on the slag viscosity.

It may be remarked here that this last factor in particular affects not only the reaction between the gas and slag, but also that between the slag and metal, and limits the convection currents, which no doubt play a great part in the transference of iron oxide (Fe_2O_3) to the metal. For these reasons the viscosity of the slag has a most important influence upon the rate of gas-oxidation.

7. *The Function of Ferric Oxide in Gas-Oxidation—Reactions between Ferric Oxide and Silica.*—The oxidation of the slag is largely conditioned by the very important fact that at high temperatures Fe_2O_3, either free or when dissolved in a silicate melt, undergoes dissociation with the formation of FeO, oxygen being liberated. Pure Fe_2O_3 dissociates under atmospheric

pressure at about 1350° C., and the new compound formed is stated to be magnetic.[1] In an experiment described below where a scale containing 23 per cent. of Fe_2O_3 was heated well above its melting point in the gases of an oxygen furnace, the melt was found to contain 17 per cent. Fe_2O_3. It may therefore be concluded that the melts derived from Fe_2O_3 form a series with varying contents of this substance, the proportions obtained depending on the temperature and on the oxidising power of the gases.

When silica is also present in the melt, the equilibrium between the two oxides of iron under a given gas will in general be altered to an extent dependent on the silica content. The existence of such a relationship has recently been indicated by McCance[2] as the result of the examination of mill cinders. If a comparable series is to be obtained by this means it is necessary that all the samples should be taken from furnaces working under the same conditions as regards gas and temperature. The following series taken from mill soaking pits where the conditions were very fairly constant affords a good illustration of the influence of silica on the equilibrium between ferrous and ferric oxides:

	SiO_2.	FeO.	Fe_2O_3.
	Per Cent.	Per Cent.	Per Cent.
1	7·8	63·1	26·5
2	22·6	56·8	15·7
3	32·0	57·8	7·1
4	34·8	57·1	6·0

In order to obtain further evidence on this question, series of experiments were made in which samples of mill scale containing about 25 per cent. of Fe_2O_3 were mixed with varying amounts of silica and heated in an oxygen furnace. Melts of about 25 grammes and about ¼ inch deep were made in uncovered platinum crucibles, and so were exposed to the burnt gases. In both series the pressures of oxygen and gas used were kept constant throughout, and the furnace was allowed to become thoroughly hot before the first sample was put in. The order in which the mixtures were melted was varied in order to guard against any errors which might arise owing to a gradual increase in the furnace temperature during the experiments. Each melt when withdrawn from the furnace was rapidly cooled under water so as to avoid, as far as possible, oxidation by the air while cooling. In both series the period of heating given was ten minutes after complete fusion had occurred; experiments made both with shorter and longer periods indicated that this time was approximately sufficient for the establishment of equilibrium with the gases. In the first series the temperature was about 1400° C., and the following results were obtained:

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[1] J. Walden, *American Chemical Society*, 1908, vol. xxx. p. 1350.

[2] *Loc. cit.*

	SiO_2.	FeO.	Fe_2O_3.	FeO/Fe_2O_3.
	Per Cent.	Per Cent.	Per Cent.	
1	...	85·4	13·5	6·3
2	15·0	77·0	7·5	10·3
3	25·0	66·8	6·9	9·7
4	35·0	60·4	3·1	19·5

The second series was made at a somewhat higher temperature, more oxygen and gas being used. The results are given below:

	SiO_2.	FeO.	Fe_2O_3.	FeO/Fe_2O_3.
	Per Cent.	Per Cent.	Per Cent.	
1	...	80·7	17·5	4·6
2	15·0	69·8	13·4	5·2
3	25·0	62·5	10·8	5·8
4	35·0	58·9	4·8	12·3

The results of the above series are plotted below in a triangular diagram (Fig. 3), in which the three variables are FeO, Fe_2O_3, and SiO_2. The three lines so obtained converge toward a point on the SiO_2–FeO line at about 57 per cent. FeO. The experimental data show that after a certain point the addition of silica exercises a very strongly marked action in reducing the amount of Fe_2O_3 present. Further work on this interesting and important system is greatly needed.

The shape of these curves is not consistent with the assumption that the silica acts simply as a diluent, and the explanation of the rapid diminution of the Fe_2O_3 must be sought in the constitution of the melted silicates. In the view of Vogt, "The silicate melts are crystalloid reciprocal solutions of stoichiometric compounds; namely, of those compounds which crystallise out upon sufficient cooling." This expression must be taken to include also molecules which do not happen to crystallise out on freezing, but which might do so if present in sufficient amount; thus it cannot be presumed that the rhodonite molecule is absent from the melts on the left side of Fig. 1, although solid rhodonite does not separate until manganese is present in larger proportion. Reactions such as that under consideration offer an independent means of investigating the chemical constitution of melts containing FeO. The shape of the curves given in Fig. 3 would seem to indicate that FeO forms a stable silicate molecule which is oxidised with more difficulty than the free oxide. It will be shown later (p. 236) that ferrous silicate melts are also difficult to reduce.

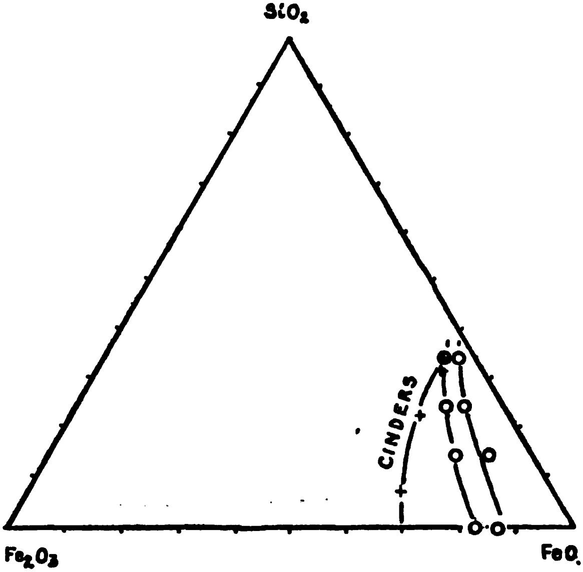

Fig. 3.—Composition of Melts containing SiO_2, FeO, and Fe_2O_3 in contact with furnace gases under varying conditions (three series).

In the investigation of the reactions between slags and gases it will be necessary to consider the solubility of the gases in the melts. Analyses made at the instance of Sir I. Lowthian Bell[1] showed that the gases evolved from blast-furnace slags in cooling have a composition generally resembling that of the furnace gases. The presence of dissolved gases in ordinary acid slags is proved by the porosity which they occasion in the centre of the slag-ball. In the experimental melts just described the presence of dissolved gases was clearly shown, especially in those melts which contained 15 and 25 per cent. of silica; after the surface layer had crystallised, the evolution of gas from the interior caused the expulsion of some underlying molten slag which flowed over the surface. It would seem that the gas solubility may vary according to the acidity and perhaps the nature of the bases present.

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[1] "The Manufacture of Iron and Steel," 1884.

8. *The Ferric Oxide Content of the Slag during the Process.*—The experimental evidence just given clearly shows that the maximum amount of ferric oxide which can be present in an acid slag at any period will depend upon the temperature, composition of the slag, and oxidising character of the gases passing through the furnace. The equilibrium composition of such a melt in contact with an oxidising atmosphere is reached by a fairly rapid reaction, and in all probability the amount of ferric oxide in the ordinary slag under working conditions can never exceed 4·0 per cent. This limiting quantity will only be attained in the absence of reduction by metal or gas. The analysis of acid slags taken at various stages of the "boil" invariably shows that the content of Fe_2O_3 is much lower than the above figure,—in fact, it seldom exceeds 0·4 per cent.; the accumulation of this compound in the slag during this period must inevitably be prevented by the reducing action of the metallic globules and possibly by the presence of CO. It might be supposed that the Fe_2O_3 content of the slag would be raised for a time by the addition of a large quantity of Fe_2O_3 (as ore) to the bath. This was not found to be the case; the quantities of the two oxides of iron in samples of slag taken immediately before and after the addition of 10 cwt. of purple-ore bricks are given below:

	Per Cent.	Per Cent.
Before ore addition	FeO 26·7	Fe_2O_3 0·30
After " "	FeO 33·7	Fe_2O_3 0·30

On the amount of slag present the maximum increase of Fe_2O_3 should have been 8·5 per cent., but this has here appeared as FeO.

In the above instance the furnace had settled on the "boil," the carbon being about 1·50 per cent. When a similar addition is made at an earlier stage it frequently causes no increase of iron, either ferrous or ferric, in the slag. The condition of the bath before boiling is such that probably no definite line of separation exists between metal and slag; the rapid reduction of ore at this stage is no doubt due to the powerful action of the silicon which is being removed from the metal.

Experiments such as the above clearly show that Fe_2O_3 is very rapidly destroyed in the slag by the reducing actions. At the temperature of the furnace, even in the absence of reducing agents, any excess of Fe_2O_3 added as ore must be rapidly decomposed by means of the reaction with silica, described in the preceding section; this decomposition could, however, only proceed as far as the equilibrium content, which appears to be about 4·0 per cent. The fact that the actual amount retained is far below this must be regarded as conclusive proof that Fe_2O_3 in the acid slag is extremely active as an oxidising agent. The rapidity with which Fe_2O_3 is destroyed makes it seem possible that, during a heavy feed of ore, an appreciable quantity of free oxygen may be liberated.

The amount of Fe_2O_3 in the slag is constantly being raised by the absorption of oxygen at the upper surface, owing to the tendency of the slag to reach equilibrium with the gas. Through the circulation of the slag and the movement of the metallic globules contained in it, the newly formed Fe_2O_3 is continually being brought into contact with the metal, by which it is quickly destroyed. Thus the Fe_2O_3, although present in such small amount, must play an important part in the gas-oxidation.

Direct evidence of the constant formation of Fe_2O_3 can be obtained in the finishing period when the carbon has diminished to below 0·30 per cent. At this stage the volume of CO passing through the slag is greatly lessened, and the metallic globules are no longer held in suspension in any quantity. As a consequence the Fe_2O_3 is not reduced as rapidly as it is formed and the amount present begins slowly to increase, more especially in slags not containing lime, and this causes the colour of the quickly cooled slag to become gradually darker. The following example, showing the increase in Fe_2O_3 in a series of samples taken during a period of about one hour, will serve to illustrate this effect:

	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Carbon in metal	0·28	0·24	0·20	0·14
Fe_2O_3 in slag. . . .	0·20	0·28	0·85	1·71

The highest amount yet found in a finishing slag was about 3·0 per cent. This increase can obviously be attributed to the diminution of the carbon content of the bath and consequent slackening of the reducing actions. The darkening in colour of the quickly cooled slag sample caused by the rise in Fe_2O_3 affords the smelter a very useful indication of the condition of the bath as regards its carbon content.

9. *Reactions between Metal and Slag.*—The number of possible reactions by which the carbon of the metal may be removed by the slag is considerable. Those in which CO_2 is a product in all probability play a very subordinate part, however, and for the present purpose it will be sufficient to consider only the three reactions in which CO is produced. These are given below, together with a fourth reaction, in which metallic iron is oxidised by its higher oxide:

(1) $FeO + C = CO + Fe.$
(2) $Fe_2O_3 + 3C = 3CO + 2Fe.$
(3) $Fe_2O_3 + C = CO + 2FeO.$
(4) $Fe_2O_3 + Fe = 3FeO.$

The complete determination of the relative velocities of these reactions in the furnace is not yet possible, but certain general conclusions may be drawn from the changes in the slag analyses at the finishing stages. The above reactions differ in their effect on the total iron content of the slag; No. 3 causes practically no change; Nos. 1 and 2 lower the iron, while No. 4 is the only reaction possible by which the percentage of iron can be increased. In the later stages of the process, when the carbon has fallen below 0·15 per cent., the iron content of the slag, after being stationary for a time, may actually rise, as shown below, without any further ore addition being made:

Time.	10.45.	11.0.	11.20.	11.40 A.M.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Carbon in bath	0·14	0·12	0·10	0·08
Iron in slag	26·3	26·3	27·0	27·6
Ferrous oxide in slag	32·5	32·3	32·8	33·2
Ferric oxide in slag	1·45	1·7	2·1	2·57

This increase must be due to the predominance of reaction (4) over reactions (1) and (2), while the constancy attained previously was due to a balance, the total rates of (1) and (2) at this period being closely equal to that of (4). There can be little doubt that during the "boil" reaction (4) between the molten iron and the ferric oxide still occurs, but is masked by the greater speed of the carbon reactions (1) and (2), the net result being a diminution of the FeO in the slag. It should be remarked here that the variation in the area of reacting surface, due to the presence or absence of metallic globules in the slag, will affect all the reactions equally, so that their relative rates will not be disturbed from this cause.

It is of interest to note that reaction (4) also occurs when solid iron is present in a melt containing Fe_2O_3. About 20 grammes of mill cinder (30 per cent. SiO_2) was placed in a platinum crucible and melted in an oxygen furnace. A piece of pure iron weighing 1·40 gramme was then quickly pushed beneath the surface and the heating continued at about 1400° C. for fifteen minutes, after which time the melt was rapidly cooled. On crushing, no trace of the metallic iron could be found, and the iron content of the cinder had increased from 47·2 to 49·0 per cent. There can be no doubt that this reaction plays an important part in the formation of scale on the surfaces of ingots, slabs, &c., when in the soaking pits.

The oxidation of the carbon by the slag takes place by reactions (1), (2), and (3). The first depends upon the concentration of the FeO, while the other two will depend upon that of the Fe_2O_3. Seeing that the proportion of the former oxide to the latter is generally greater than 100 to 1, and even at the end of the process is usually more than 10 to 1, it is evident that if any considerable part of the oxidation is performed by the Fe_2O_3 the rate of reaction (1) must be very much less than that of (2) and (3). A strong reason has already been given (p. 233) for believing that this is the case, for on addition of Fe_2O_3 to the bath this oxide is at once destroyed, while the FeO increases. Several other considerations can be advanced which all point to the conclusion that the greater part of the carbon oxidised by the slag is removed by the Fe_2O_3,[1] according to equations (2) and (3), and only a small part by the FeO, according to equation (1).

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[1] The possibility that Fe_2O_3 may play an important part as a carrier of oxygen was first suggested by Dr. Stead. *Journal of the Iron and Steel Institute*, 1897, No. I. p. 134.

(*a*) Percy[1] endeavoured to reduce a melt of fayalite composition by carbon, and only succeeded in obtaining a melt having a similar composition to a ferruginous acid slag. He was unable to effect the complete reduction of FeO in the presence of excess silica.

(*b*) It is well known that during the "boil" the thickening of the slag through removal of the FeO is accelerated by the action of a good flame on the surface. This may well be connected with the more rapid oxidation of the FeO in the slag through the action of the hot flame, the Fe_2O_3 so formed being then reduced to metallic iron by the carbon.

(*c*) In a series of interesting experiments, Hatfield and McWilliam[2] found that a considerable reduction of silica could be obtained under suitable conditions even in the presence of 21·0 per cent. of FeO. Had it been possible to reduce the FeO rapidly this should have occurred in preference to the reduction of silica.

(*d*) The great difficulty with which FeO is reduced in a siliceous slag is very well shown in the above-mentioned experiments, in which a furnace was held for over two hours without ore additions, the slag becoming very thick. During this time the carbon dropped from 0·86 to 0·38 per cent., while the FeO in the slag was only lowered from 24·0 to 20·8 per cent. Thus, although the slag was in contact with a metal fairly rich in carbon, no great loss of FeO had occurred, most of the carbon having been eliminated by gas-oxidation. Similar results have been obtained by the authors.

These considerations all indicate that in the presence of a high silica content, such as occurs in the acid slags, the reduction of the FeO is very slow, so that the amount of carbon removed by reaction (1) is comparatively small. It follows that if a charge covered with an ordinary slag could be held in a neutral atmosphere the slag would thicken only very slowly and the elimination of the carbon would be greatly retarded. This effect may possibly be due to the existence of a stable silicate of iron in the molten slag. That the oxidation of the carbon by the slag during the "boil" is rapid is evident from the manner in which the slag quickly thickens after a feed of ore. As the reduction of FeO appears to be so slow, this rapid removal of iron must be attributed to the complete reduction of Fe_2O_3 formed from the FeO by gas-oxidation; the ferrous silicate must be oxidised before it can be easily reduced to form metallic iron. It is thus clear that the rapid working of the charge is dependent to a large extent on the degree to which gas-oxidation occurs. The use of a rich gas with as much air as the furnace can carry will afford the best conditions for the rapid thickening of the slag, so permitting an increased frequency of ore additions which will accelerate the removal of the carbon.

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[1] W. H. Greenwood, "Steel and Iron," 1893, p. 56. See also discussion by H. Louis on Paul's paper, *Journal of the Iron and Steel Institute*, 1912, No. II. p. 105.

[2] *Journal of the Iron and Steel Institute*, 1902, No. I. pp. 54–62.

10. *Oxidation by Direct Contact of Metal with Gas.*—The preceding remarks have been concerned entirely with the transmission of oxygen to the metal by way of the slag. During the "boil," however, the slag is highly charged with metallic iron, and the possibility of oxidation by direct contact of metal with gas must also be considered. That gas-oxidation actually does occur by this means is clearly seen by comparing the rate at which oxygen is absorbed from the gas during the boiling period (1) with that during the finishing period (2).

(1) It has already been shown (p. 226) that more than 50 per cent. of the carbon present on melting is removed during the subsequent working by gas-oxidation. This figure includes the amount eliminated in the finishing period when the slag is practically free from metal, but since the quantity of carbon removed in the later stage is relatively small the same ratio of gas-oxidation may be held to apply to the boiling period taken by itself, and the rate of removal of carbon by this means will be about 0·30 per cent. per hour.

(2) As soon as the metal has dropped off the "boil" the metallic globules are no longer held in suspension, and oxygen from the gas can then only reach the metal through the slag. The amount of oxygen taken from the gas at this stage may readily be calculated from analyses of slag and metal samples; the following will serve as an illustration. The last feed of ore was given to a 100-ton charge when the carbon was about 0·28 per cent. After the reaction had subsided samples of metal and

slag were taken at intervals until the carbon had been reduced to 0·12 per cent. The results of the analysis of these samples are given in the table below:

Time.	11.5.	11.15.	11.27.	11.45.	12.0 A.M.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Carbon in metal . . .	0·24	0·22	0·19	0·15	0·12
Ferrous oxide in slag . .	31·2	30·90	30·50	29·4	29·3
Ferric oxide in slag . .	0·35	0·30	0·55	0·60	0·85

The finishing slag weighed about 12 tons and had the following analyses: SiO_2, 54·3; FeO, 29·3; MnO, 10·10; CaO, 3·4; MgO, 0·80 per cent. From these figures the amount of oxygen taken up can be obtained as follows:

(1) In the formation of Fe_2O_3 in slag about . . .	0·018 ton
(2) In the elimination of 0·12 per cent. carbon . . .	0·160 „
Total	0·178 „

From this total 0·055 ton must be deducted, owing to removal of FeO from the slag. The amount of oxygen absorbed in fifty-five minutes by gas oxidation was therefore 0·123 ton, which would be sufficient to remove 0·10 per cent. of carbon per hour, while during the boiling period the average drop in carbon exceeded 0·50 per cent. per hour, of which about 0·30 per cent. per hour was removed by gas-oxidation. It is probable that the figure found for the end period is on the low side, owing to the comparative quietude of the slag, the lower content of FeO and higher content of Fe_2O_3, which would all tend to reduce the rate of absorption. Even when all possible allowance is made for such points as these, and for a probable small increase of FeO in the metal, it seems certain that the amount of gas-oxidation occurring during the "boil" was at least twice as much as that in the finishing stage, and as the area of the bath and the average composition of the slag remained about the same throughout, the greater rate during the "boil" must have been caused by the direct contact of the metal with the gas. This contact is effected in two ways:

(1) The violent agitation, brought about by the addition of large lumps of ore, often causes quantities of metal momentarily to flow over the surface of the slag.

(2) A still more important action must be due to the very numerous globules of metal which are constantly entering the surface layer of the slag, where they will be rapidly oxidised, even if they do not actually come into open contact with the gas.

11. *The Effect of Lime Additions on the Rate of Gas-Oxidation.* —It is well known that the presence of a considerable amount of lime in the slag retards the rate of removal of the carbon, especially in the finishing stages. As has just been shown, the oxidation of the carbon, after the metal has dropped off the "boil," takes place by way of the slag and not by direct contact; since the activity of the metal in reducing the slag is not affected by lime additions, the retardation must be attributed to a diminished capacity of the slag for absorbing oxygen. This view would require that, under equal conditions, a limey slag should contain a lower amount of Fe_2O_3 than one not containing lime. The following two analyses of finishing slags which were obtained under comparable conditions show that this is indeed the case:

	C in Bath.	SiO_2.	FeO.	MnO.	CaO.	Fe_2O_3.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
1	0·13	52·8	30·1	10·2	0·8	1·70
2	0·12	50·6	21·9	10·5	13·8	0·30

It is clear that the diminution of the Fe_2O_3 content in No. 2 sample cannot be due simply to the lower content of FeO; the capacity of the slag for absorbing oxygen has evidently decreased independently of this. Slags of intermediate lime content are generally intermediate in their Fe_2O_3 content when taken at the same stage as the above; an example is to be seen in the slag analysis given on p. 226. The diminution of the Fe_2O_3 content in the presence of lime corresponds with the reduced oxidising power of these slags. Not only is the carbon removed more slowly, but the oxidation of the iron according to reaction (4), p. 234, is also greatly retarded. This is indicated by the fact that the increase in total iron which may occur in ordinary slags at the finish through the above reaction is seldom, if ever, obtained when lime is used in any quantity.

The action of lime in suppressing the gas-oxidation of the slag is of great practical value in the production of that state of the bath known as the "dead melt." When a perfectly dead melt is obtained the carbon content of the metal becomes nearly stationary, a condition in which it is clear that gas-oxidation has almost entirely ceased. According to the views here advanced, by suitable lime additions the rate of the formation of Fe^3O_3, and consequently the rate of gas-oxidation, can be greatly retarded. In the absence of further ore additions this retardation leads to a gradual slackening of the reaction; as a consequence, the metallic globules fall from the slag and so oxidation by direct contact also ceases. An opportunity is thus given for the completion of those reactions occurring in the body of the metal which lead to the production of the dead

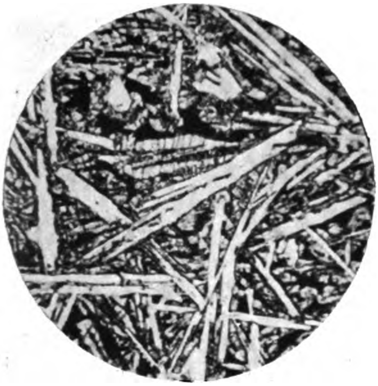
SUMMARY.

The paper is divided into three sections, dealing respectively with the microstructure of slags, the structure of the hearth, and the reactions occurring in the molten slag during the process.

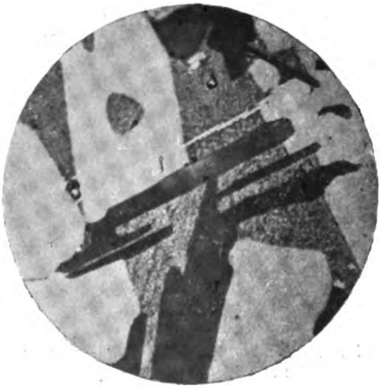
Part I. The Microstructure of Acid Slags.

1. The minerals present in slowly cooled acid slags without lime are tridymite, cristobalite, fayalite, and rhodonite; the last named contains the bases in very nearly the same ratio as the melt. The silica minerals freeze first, but super-cooling always occurs to some extent. They are followed by fayalite or rhodonite, the silicate formed being determined by the ratio of iron oxide to manganese oxide; when this exceeds 73:27 fayalite is formed; in other cases, rhodonite. In slags containing more than about 8 per cent. of lime, an anorthic metasilicate of CaO, FeO, MnO, MgO is obtained, which has a brilliant cleavage and gives rise to a marked acicular fracture in the slag.

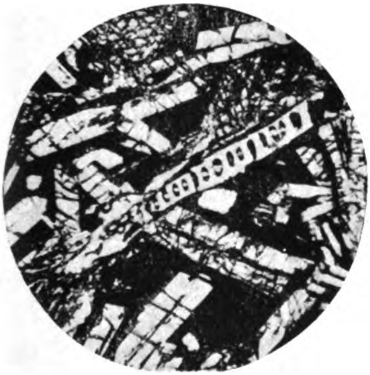
2. The order of freezing of the minerals in a number of slags whose analyses are given is represented in a ternary diagram, which is approximately that for the system $FeO-MnO-SiO_2$. A qualitative diagram is also given to illustrate the binary system $FeO-SiO_2$.



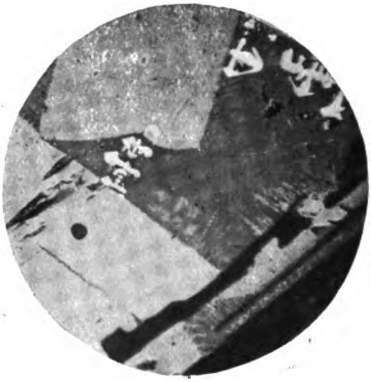
No. 1. × 85. Acid slag; tridymite in groundmass of fayalite, &c.



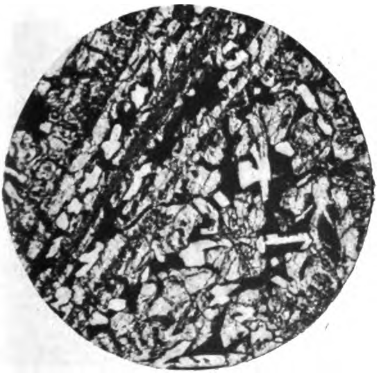
No. 2. × 425. The same, polished section.



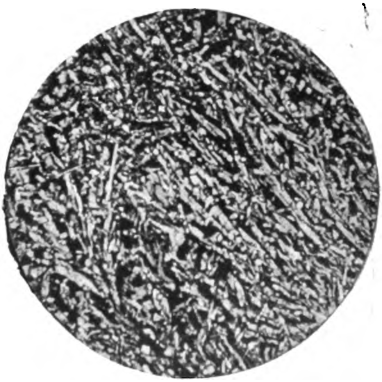
No. 3. × 85. Acid slag; cristobalite in groundmass of rhodonite, &c.



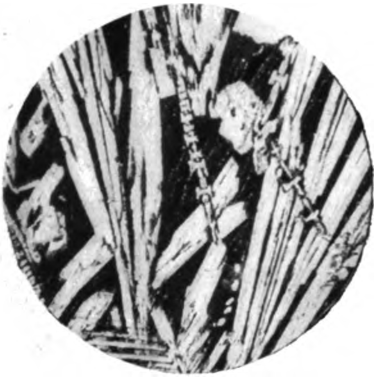
No. 4. × 425. The same, polished section.



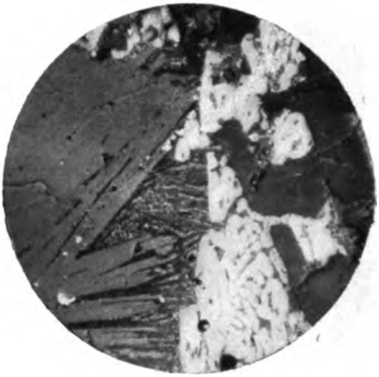
No. 5. × 90. Eutectic of silica and fayalite with brown glass.



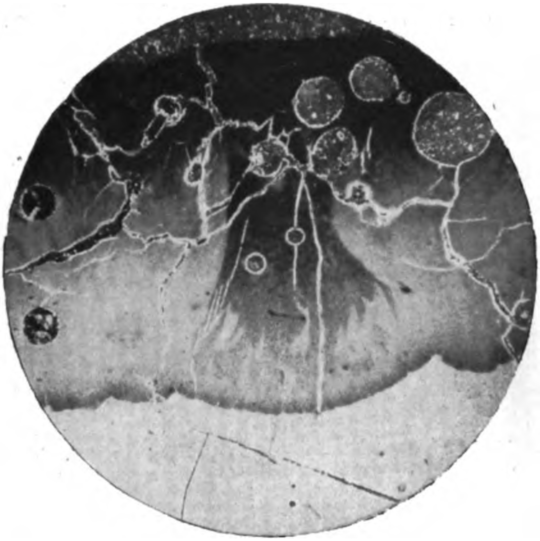
No. 6. × 85. Section through a nodule from an acid slag; tridymite, cristobalite and rhodonite.



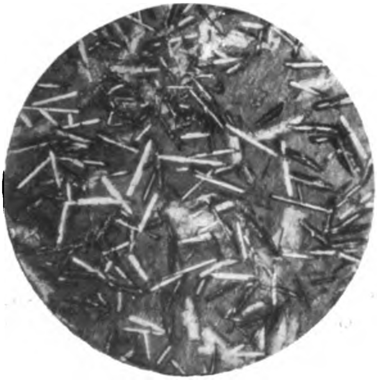
No. 7. × 35 Acid slag; cristobalite in metasilicate and glass.



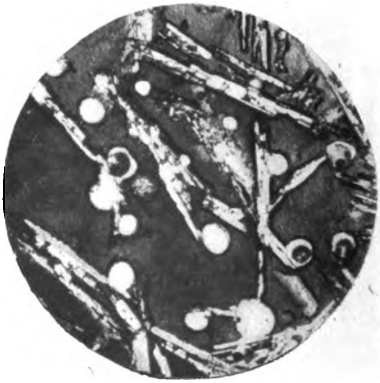
No. 8 × 425. The same; polished section; cristobalite, metasilicate, fayalite and glass.



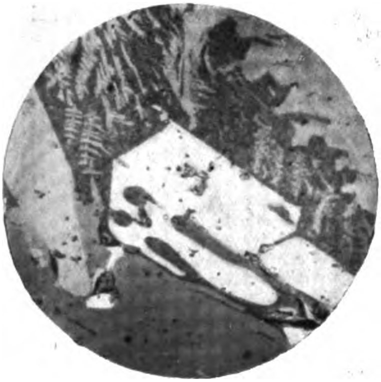
No. 9. × 20. Acid slag; spoon-sample. Thin section in oblique illumination.



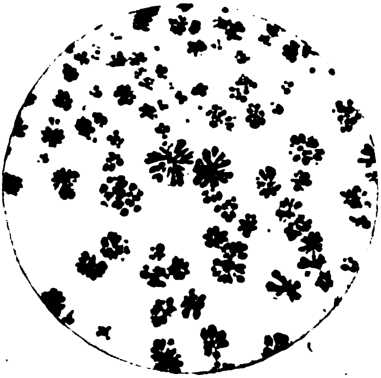
No. 10. × 35. Acid slag; spoon-sample, reheated at about 1200°C. for 18 hours.



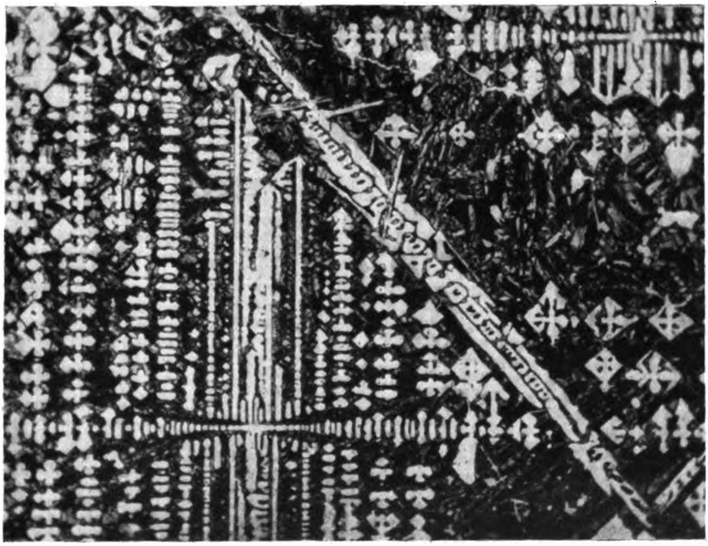
No. 11. × 35. Acid slag; sample 1 reheated at about 1200°C. for 18 hours.



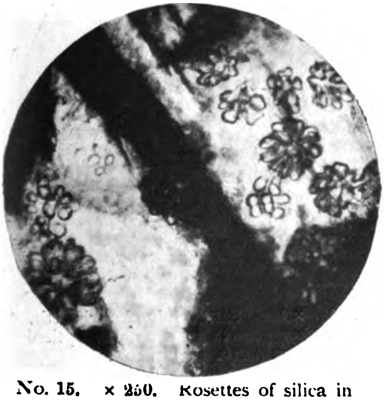
No. 12. × 425. Acid slag, polished section; rhodonite, fayalite and glass.



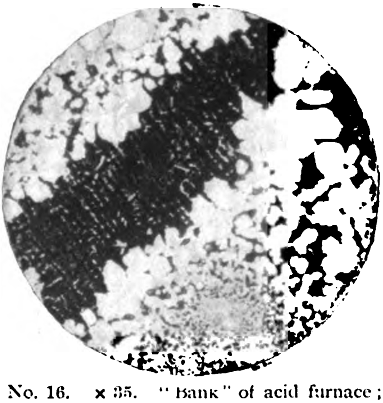
No. 13. × 425. Acid slag, spoon-sample, polished; rosettes of silica in glass.



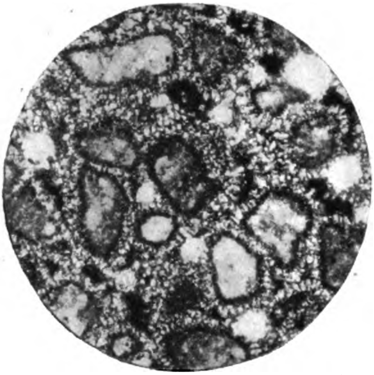
No. 14. × 20. Acid slag; cristobalite in ground mass of fayalite, &c.



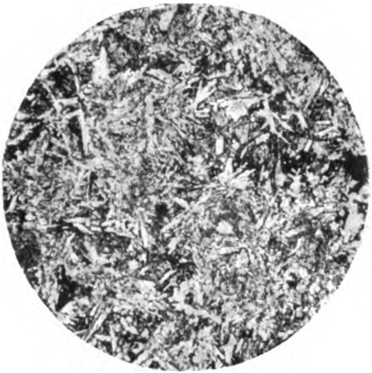
No. 15. × 250. Rosettes of silica in rhodonite and glass.



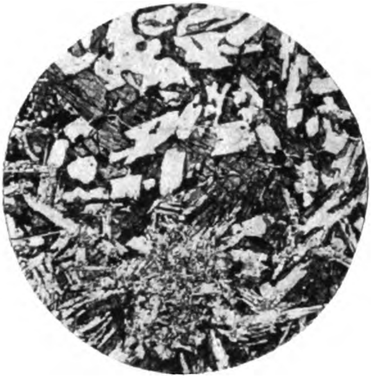
No. 16. × 35. "Bank" of acid furnace; cristobalite with magnetite, &c.



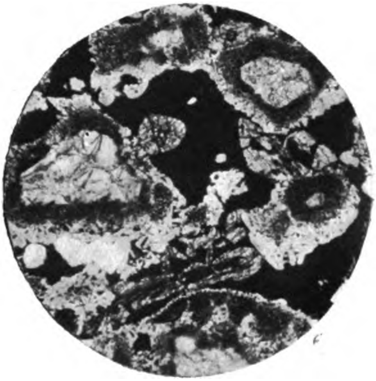
No. 17. × 85. Freshly-made patch in an acid hearth; sand-grains partially altered to tridymite.



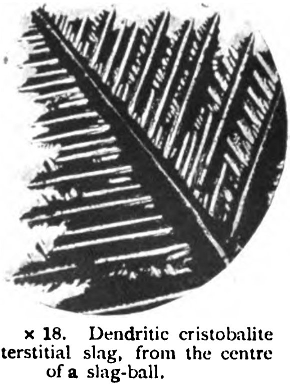
No. 18. × 85. Older portion of an acid hearth; alteration to tridymite completed.



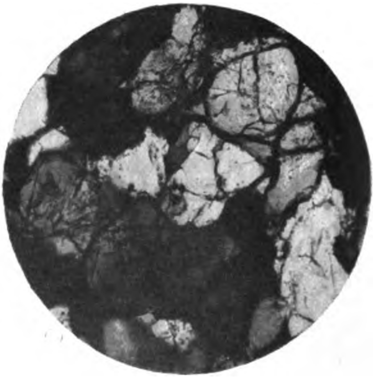
No. 19. × 85. Surface of acid hearth; tridymite passing into cristobalite, with fayalite.



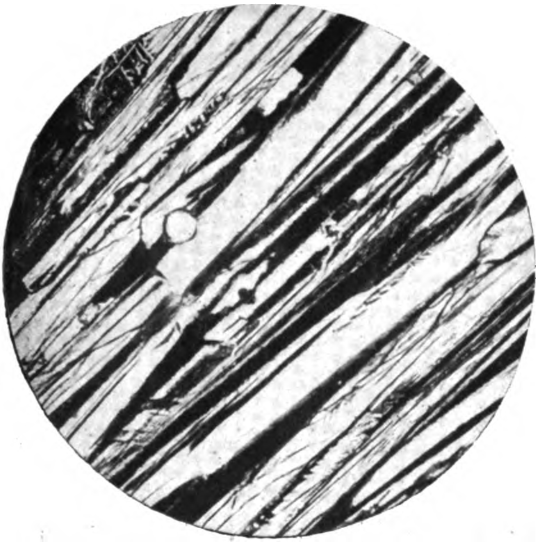
No. 20. × 85. Lower part of hearth next brickwork; gannister and sand in slag with fayalite



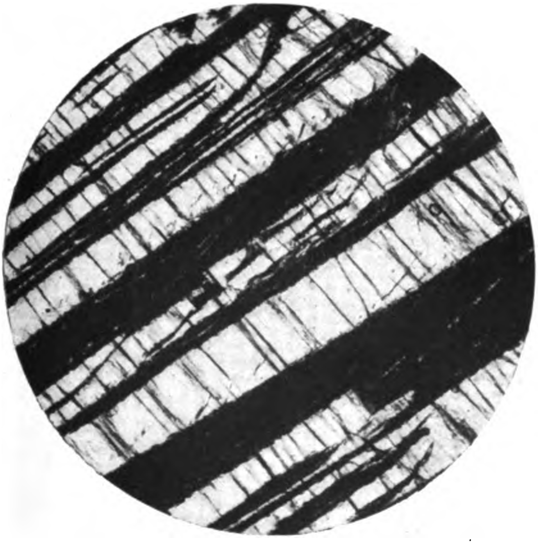
No. 21. × 18. Dendritic cristobalite with interstitial slag, from the centre of a slag-ball.



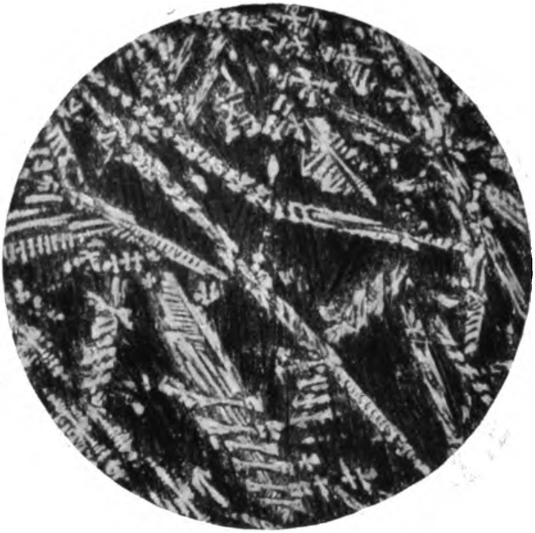
No. 22. × 80. Sand-grains from hearth, with further growth of quartz in optical continuity. × d nicols.



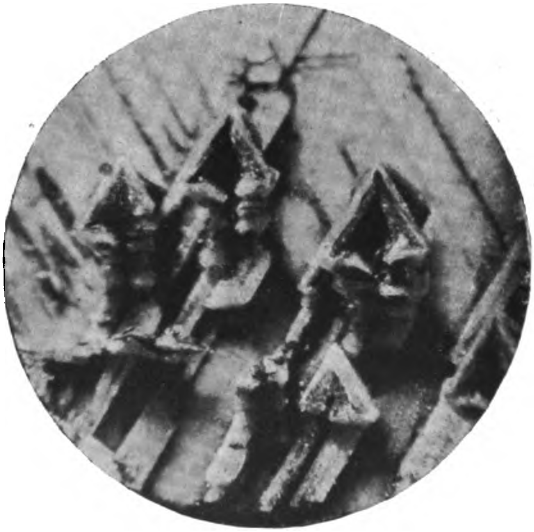
No. 23. × 20. Acid slag; anorthic metasilicate with brown glass.



No. 24. × 20. Acid slag; rhodonite with brown glass containing narrow crystals of fayalite.



No. 25. × 20. Acid slag; cristobalite in a ground mass of fayalite and glass



No. 26. × 15. Skeletal octahedra of cristobalite in parallel growth on a plate of the same mineral.

To face p. **241.**

3. Acid slags after being reheated for eighteen hours at 1300° C. contain free tridymite, and resemble the furnace hearth in structure.

4. Spoon samples taken from the furnace are superficially oxidised to a depth which depends on the nature of the slag, and is least when the silica is high or when lime is present. The dull lustre of fractured glassy samples is due to minute particles of silica.

PART II. THE ACID HEARTH.

5. A number of analyses show that the hearth contains only 70 per cent. of silica, although the sand used is required to contain at least 96 per cent.

6. Microsections show that the upper layer consists mainly of interlacing plates of tridymite with interstitial slag; in the lower and cooler parts the quartz grains are less altered. The penetration of slag extends down to a well-defined limit, usually in the brickwork. The relatively small depression of the freezing point of silica in the presence of impurities is no doubt an important factor in the stability of the hearth.

7. The effect of impurities in the sand is complex; apart from softening the bank, they give rise to caking and so prevent the absorption of the fluid slag on the bottom by the new sand —an action which is essential for the satisfactory repair of the hearth.

8. The amount of ferric oxide in the hearth is considerably lower than that in the surface layers. This may be due to reduction by CO or metal, and to reaction with the silica present.

PART III. THE MOLTEN SLAG.

9. The adjustment of the slag by the smelter to the required degree of viscosity, and the manner in which the iron content is reduced by lime additions, are described.

10. The proportion of carbon removed by gas-oxidation is estimated from experimental data for casts with and without lime additions. Between melting and tapping at least half the carbon is so oxidised, and this proportion is not greatly altered when lime is used.

11. The physical conditions under which the molten slag reacts are discussed, and it is shown that during the "boil" one-half per cent. of the metal is suspended as small globules in the slag, so that the reacting surface is greatly increased.

12. The view is advanced that gas-oxidation takes place—(1) By the formation and reduction of Fe_2O_3 in the slag; (2) by direct contact of the metal and gas.

13. Experiments are given to show that the proportion between ferrous and ferric oxides in a melt is determined by the silica content, the temperature, and the nature of the gases. In acid slag under ordinary furnace conditions the maximum (in the absence of reduction by the metal) appears to be about 4 per cent.

14. Throughout the "boil" the content of Fe_2O_3 remains very low (0·3 per cent.), but may increase in the finishing period as far as 3·0 per cent. It is clear that the Fe_2O_3 must be very rapidly destroyed by the reducing action of the metal, which slackens as the carbon content falls and so permits the increase of Fe_2O_3 at the finish.

15. The relative rates of various possible reactions between slag and metal are discussed. The constancy of composition of the slag in the later stages is due to a balance between the oxidation of iron from the metal, and the reduction of iron from the slag by the carbon. In an acid slag the latter reaction probably takes place mainly through the direct reduction of Fe_2O_3 rather than by the reduction of ferrous silicate.

16. Of the carbon removed from the metal after melting, roughly one-half is removed by the ore, one quarter by gas-oxidation through the slag, and one quarter by direct contact between metal and gas.

17. The effect of lime in the slag is to lower the Fe_2O_3 content; this action is probably of great value in protecting the metal from oxidation during "dead melting."

DISCUSSION.

Mr. E. H. **Saniter** (Rotherham) said that the paper was exceedingly interesting, and gave a good deal of valuable information. He had also greatly admired the beautiful photomicrographs of the slags. Owing to the war, everybody had had to readjust their ideas with regard to the sand used in the Siemens furnace. He saw the authors considered—and he thought rightly—that it was necessary to have a fairly high percentage of silica in the sand used, although the bottom might contain less silica than the sand added to it. His own experience was that before the war too much insistence had been placed on a refractory sand. Sand was used which was so refractory that it was very difficult to flux properly, and consequently gave more trouble than it ought to have done. Since the war he had mixed two sands which would average 97 per cent. silica. An inferior and a better sand had been mixed in equal proportions, and much better results had been obtained in the bottoms than had been obtained with Belgian sand as used before the war. The authors' statements as to the use of limestone, and its retarding effect on the formation of, he would not say peroxide of iron but of magnetic oxide in the slag at the end of the operation, raised a very important point. Perhaps people were unaware that it was the limestone that had a retarding action, and therefore a valuable bearing on the making of steel, by securing that retarding action of the limestone on the formation of magnetic oxide towards the end of the operation. With regard to the calculations of the amount of oxidation caused by ore and by air, there was an instance given of slag being 25 per cent. in iron right through. He had been wondering whether a great deal of the oxidation did not occur at the early stage of the slag, or whether perhaps in that particular calculation that had been overlooked. Later calculations, he knew, took that point into consideration.

Dr. F. **Rogers** (Sheffield) considered that the research work on the constitution of the hearth and slag, recorded by the authors, especially if studied in conjunction with the valuable paper by Dr. McCance[1] on non-metallic inclusions, formed a most useful store of knowledge for which the need existed in the study of many steel problems. Obviously it was not possible for every worker to carry out such general studies for his own immediate needs; he had been able to work at portions of the field from time to time as occasion demanded. In particular he had directed his attention to minimising the amount of iron oxide in the metal towards the end of the melting processes, and to the minimising of non-metallic inclusions. He had previously indicated conditions which specially conduced to the minimising of iron oxide in the acid open-hearth bath at the end of the boiling down, and he would emphasise the importance of doing so as thoroughly as possible previous to the addition of deoxidisers. In the case of bottom run ingots in particular, owing to the molten metal having washed over fireclay surfaces in contact with hot air, as well as in steel in general, instances often arose in which it was most important to decide whether non-metallic inclusions had been due to that contact with refractory materials, or to furnace slags, or to their formation *in situ* during casting and solidification. Analyses of small, but significant, inclusions were often almost impossible. Systematic data as to microstructure of the non-metallic matters, such as was given by the authors and by Dr. McCance, was therefore very valuable. The fluxing of several of the principal refractory materials in contact with molten steel and slag, and under furnace wall and roof conditions, yet remained to be fully studied in order to complete the knowledge possessed of that series of associated problems.

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[1] *Journal of the Iron and Steel Institute*, 1918, No. I. p. 239.

Dr. A. McCANCE (Glasgow) said he would only deal with one of the many questions raised in the authors' very original paper, and that was the rôle which atmospheric oxidation of the slag played in removing the carbon. They ascribed it to Fe_2O_3 formed by direct oxidation of FeO and acting as a carrier of oxygen from the air to the molten bath of metal. Although such action was admitted by him, he did not think that Fe_2O_3 played any part in it as such, but that the real carrier of the oxygen was Fe_3O_4. The presence of magnetite in open-hearth slag which he had first noticed and Mr. Whiteley confirmed, gave obvious support to that view, but there were other reasons as well. When considering the question some time ago he (Dr. McCance) had been anxious to discover whether open-hearth slag was oxidised by air, and for that purpose some finely ground slag was heated in a current of air at gradually increasing temperatures, and the increase in weight measured. The sample contained to begin with 12·02 per cent. FeO and 0·80 per cent. Fe_2O_3, and the increase in weight commenced at 500° C. and reached a maximum at about 1100° C., at which temperature the iron had become almost wholly ferric, an actual analysis giving 0·50 per cent. FeO and 14·40 per cent. Fe_2O_3. The slight difference in the iron content of the two samples was due to the fact that the samples were taken at different times from two lots of the same slag crushed separately. In the first case the increase in weight occasioned by the conversion of all the ferrous iron into ferric would be 1·34, and in the second case it would be 1·43. Actually the weighed increase was 1·38 per cent., so that it corresponded exactly with the conversion of the ferrous iron to the ferric condition.

The slag at 1100° C. was non-magnetic but on heating higher it became magnetic, and at the same time the increase in weight decreased up to 1300° C., which was the highest temperature tried. That showed that Fe_2O_3 in air above 1100° C. was decomposed and that it was the magnetic oxide which was formed. In addition to that evidence theoretical considerations pointed to the stable oxide being the one which had the lowest dissociation pressure, and at 1500° C. the dissociation pressures were roughly

$Fe_2O_3 \rightarrow Fe_3O_4$.	$Fe_3O_4 \leftarrow FeO$.
17,000 millimetres.	0·4 millimetre.

All the evidence therefore showed that Fe_2O_3 did not exist at the temperatures of steel-making furnaces. At the same time he did not attach the same importance on that action as a source of the unaccounted oxygen as Mr. Whiteley did. He had examined in detail a great many charges and found that the unaccounted oxygen expressed as a molecular percentage of the melted weight in tons, varied from 1·5 to 2·5 per cent., and although particular attention had been paid to the point he had not found that the figures bore any relation to the ratio of slag area to charge weight. In large quick-working furnaces with shallow baths the missing oxygen was no higher on the average than in the case of deep bathed furnaces with a small area of slag. The working temperature of the charge seemed of greater importance than the area of slag. The missing oxygen really came from two sources: (1) It was carried through the slag from the air by the action of Fe_3O_4. (2) It was abstracted from the metal where it existed as FeO in solution. All the evidence he had collected on that point led him to believe that the second source was of greater importance than the first, and that it accounted for more than 50 per cent. of the total missing oxygen.

Dr. J. E. STEAD, F.R.S., Vice-President, said he had little to say except in praise. The subject of the relations between the slag and the steel in the bath required very careful study, and the paper was one of the best papers of the kind that had ever been published. Everybody who undertook research found something new. They might look for one thing and not find what was looked for, but would be rewarded by finding something else. One remarkable fact to be noted was the large amount of iron oxide in the sand bottoms of the furnace. It would have been naturally supposed that such material would melt down very easily, but as a matter of fact it was found that it stood up perfectly soundly and did not give way. Something very similar occurred in the ganister bricks of the roofs of furnaces. When heat played upon the ends of the bricks the fusible parts became liquid, and some of the oxide of iron which was caught from the floating dust in the furnace was absorbed by the brick, and ascended by capillary attraction and concentrated at a considerable distance away from the point at which it entered. There was less lime in the nose of such a ganister brick than there was in the original brick. The lime fluxed by the silica had run upwards, leaving the greater mass of silica, and a considerable quantity of iron. The structure of the nose of the brick was very similar to that of the hearth of the furnace, as it contained large quantities of an allotropic modification of silica in grains with silicate of iron between.

He would point out also it was very necessary that mineralogists such as Mr. Hallimond and metallurgists should work together in order to elucidate many of the interesting points connected with the metallurgy of iron. He was also glad to see the younger members coming forward and making such progress in knowledge. Papers from Sheffield, Glasgow, the North and East Coasts, not to mention other districts, were all doing great and progressive work. He hoped that would be an encouragement and example to other workers in our industries, and that we should continue to be the foremost of the nations of the world, in that particular branch of industry.

CORRESPONDENCE.

Dr. Henry M. Howe (New York, U.S.A.), Hon. Vice-President, wrote that the important part played by ferric oxide in spite of there being so small a quantity of it present in the slag at any given instant, was of great interest. It was indeed the very activity of its oxidising action that prevented its forming a large proportion of the whole. It gave up its oxygen so readily not only to the carbon and silicon but to the iron and manganese as well, that it could not persist in large quantity.

The authors' opinion that a very large part of the oxidation of the oxidisable elements occurred through the carrying power of iron oxide had always seemed to Professor Howe true. That carrying principle was of the widest application, both in fining or oxidising processes in which the oxygen was carried to elements to be removed, and in reducing ones, including refinings, in which the oxygen was carried in the opposite direction, from the oxides of the metals which it was desired to reduce to the carbon or other deoxidising agent. In the open-hearth process in which the oxidation had to be done chiefly by the slag, that action was of great importance. A reason additional to the cogent ones pointed out by the authors was that, whereas oxidation by ferrous oxide robbed the slag of iron oxide by reducing the ferrous oxide to metal which tended to separate quickly by gravity, oxidation by ferric oxide did not, but left the slag with as much iron oxide as before. The rapid movement due to the boil quickly re-exposed the ferrous oxide thus formed to the furnace gases and reperoxidised it, so that the cycle of carrying oxygen from gas to carbon went on continuously.

Of the greatest interest was the authors' observation at the top of p. 233, that oring at the very early stages of the process, and apparently before the boil started, often failed to increase the quantity of either ferric or ferrous oxide in the slag. That period thus linked itself with the first period of the Bessemer process, when because of the relatively low temperature and the abundance of silicon the oxidation was confined almost wholly to silicon to the exclusion of carbon. The failure of oring to increase the iron content of the slag might be due first to the abundance of carbon and silicon in the bath, which reduced the iron oxide of the ore practically as fast as it entered the slag, and second to the monopolising of the oxygen by the silicon to the exclusion of carbon, because if carbon oxidised to any appreciable extent the boil which the resultant carbonous oxide would start would in itself constitute a marked and sudden addition to the strength of the oxidising conditions, and that addition would in itself lead to an increase in the quantity of iron oxide present in the slag.

The darkening of the slag towards the end of the process noted by the authors at the bottom of p. 233 was contrary to good American and, he believed, French and Italian practice in making steel of high grade, because that darkening was proof that the metal was not losing its oxygen as it should, but on the contrary was gaining, with the inevitable result that an important part of the final deoxidation would have to be done, not by carbon as it should be because the product of the oxidation of carbon was gaseous and escaped, but by silicon, manganese, or other element, the product of the oxidation of which was molten or solid, and remained in greater or less part to injure the steel in the form of inclusions. It was held that in making acid open-hearth steel of good quality the slag should be brought to a clear yellow, suggesting canary yellow, with a greenish cast in case there was an initial manganese content of 1 to 1·50 per cent.; and that at the very end, before adding ferro-silicon, it should be brought to a grey, dashed as before with green in case of a fair manganese content. In order to bring that about the temperature during the deoxidising or refining period had to be raised to the highest which the roof could endure, the high temperature apparently increasing the deoxidising power of the carbon. Hence the rule to refine hot and cast cool, the hot refining being for the purpose of completing the deoxidation of the bath by means of carbon and thus lessening the proportion of inclusions, and the cool pouring being to enable the ingots' crust to thicken at such a rate that it would be strong enough to resist the ever-increasing ferrostatic pressure. Yet a certain amount of that cracking might be tolerated, because too cool pouring meant that the steel became an emulsion so thick that the inclusions failed to escape readily.

Mr. J. E. **Fletcher** (Dudley) wrote that the diagram of the Binary System, $FeO.SiO_2$, Fig. 2, was very welcome to all students of slag metallurgy. In a study of the puddling furnace reactions and of the working slags he surmised the presence of what appeared to be a eutectic in slags of analysis between $FeO.SiO_2$ and $2FeO.SiO_2$, Fig. 18 suggesting the nearness to a eutectic of tridymite-fayalite.

In an attempt to produce artificially slags for bottoms of reheating furnaces from mixtures of ground $CaO.SiO_2$ and $FeO.SiO_2$ slags, he found that in various mixtures a primary slag of approximately constant composition first formed and fused, running over the furnace bottom and carrying with it colonies of viscous $CaO.SiO_2$ slag. The liquid primary slag was of the order $FeO.SiO_2$ plus CaO in slightly varying proportions. The presence of P_2O_5 in later mixtures produced a still more fusible primary slag, and it proved almost impossible even at higher temperatures to produce a slag of uniform composition by melting together dry mixtures of composition corresponding to the mechanical analysis. It was only by mixing together molten portions of the primary and secondary slags that a fair approximation to the requirement was obtained.

The value of the small proportion of fayalitic material in the rich silica sand for acid hearths was obvious, and the "fritting" action it gave was, he thought, clearly proved by the authors.

He was interested in the authors' belief that the reactions between the slag and the metal were largely contact actions, and that the speed of the alloying and refining reactions were influenced by the freedom from gas bubbles and by the degree of liquidity of the slag. In a thick slag there would be, it would seem, considerable stratification, the layers being of varying composition.

The speed of the reactions appeared to be largely controlled by the temperature, the degree of slag superheat above its true fusion point rendering its constitution unstable.

That was indicated in the reference to the rôle of Fe_2O_3 in the slags as chief reducing agent. In an examination of puddling slags he also found that with increasing temperature in an oxidising atmosphere the percentage of ferric oxide increased thus:

Temperature .	1500° C.	1460° C.	1400° C.
	Per Cent.	Per Cent.	Per Cent.
Fe_2O_3 . .	10·5	8·0	6·5
FeO.MnO .	77·0	73·5	68·5
SiO_2 . .	11·5	18·5	25·0

When the SiO_2 content of such slags reached about 40 per cent. the ferric oxide disappeared.

It had been thought by many, and he supported the view, that the active refining oxides were best expressed as $FeO.Fe_2O_3$, and as such attacked the bath. The readiness with which FeO in a feebly oxidising atmosphere became Fe_2O_3, as in the "bull dog" kiln, suggested the instability, at superheated temperatures, of the oxides FeO and Fe_2O_3 in fellowship in the slags of the open-hearth.

Was it not probable that at the high temperature of the open-hearth the two oxides acted as the magnetic oxide Fe_3O_4, which might act as the oxygen carrier? The presence of magnetite crystals in many puddling slags, especially in the case of iron which had been finished too hot in the balling stage or "stewed" in the furnace,

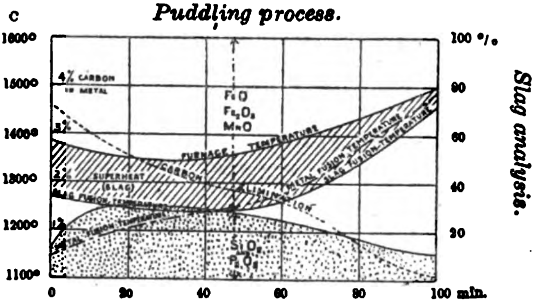

FIG. 2A.

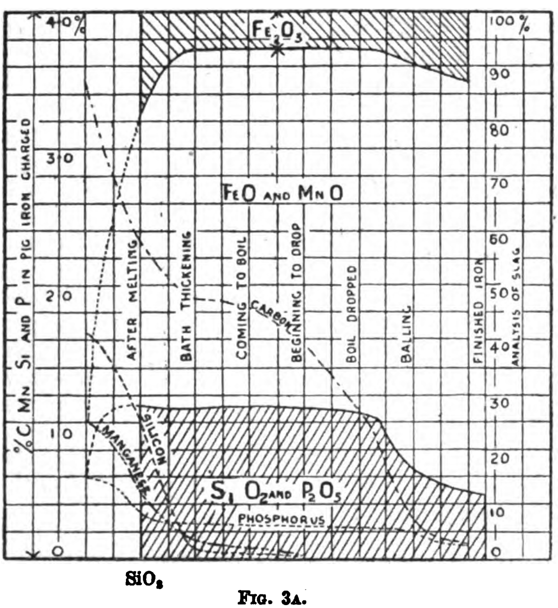

FIG. 3A.

pointed to the function of magnetic oxide at the high temperature of the acid hearth.

It was interesting to learn that the authors confirmed the work of others that CaO in the slags protected the metal from oxidation during "dead melting," and that the Fe_2O_3 content was thereby reduced.

The use of lime in puddling slags appeared to act similarly to MnO in that respect.

The diagrams Figs. 2A and 3A illustrated his points in respect to the action of superheating on slags and of the presence of Fe_2O_3 in puddling operations.

The paper of the authors was of fundamental value and was a distinct addition to our knowledge of acid open-hearth working.

It was to be hoped that they would supplement their present contribution by a similar exposition of basic working.

B. Yaneske (Sheffield) wrote congratulating the authors on the thorough manner in which they had dealt with their subject. Their discovery of a metasilicate of iron, calcium, manganese, and magnesium in limey slags was very interesting.

He (Mr. Yaneske), however, did not agree with the authors' statement that "lime additions lowered automatically the iron content of the slag by a process which was quite unconnected with any chemical equilibrium between these bases and silica." It was his experience that the addition of CaO did not lower the FeO content of the slag when there was an excess of SiO_2 present in the slag after satisfying the demands of the various bases, but formed a lime silicate ($CaO.SiO_2$), and it was not until after that occurred that CaO commenced to displace FeO from the slag.

The analysis of an acid hearth which had been in use for a considerable period (SiO_2 67 per cent., FeO 22·9 per cent., and Fe_2O_3 7·7 per cent.) showed clearly why such a great loss of metal occurred from the first charge on a new hearth, and the high percentage of Fe_2O_3 explained the liability of an old hearth to effect oxidation of the metal in contact with it, especially when the carbon was very low in the bath, whereas a newly sanded hearth had such a quietening effect on the "boil."

With regard to the view advanced by the authors that the oxidation of the greater part of the carbon by the slag was due to the reactions expressed by the equations:

$$(1)\ Fe_2O_3 + 3C = 3CO + 2Fe,$$
$$(2)\ Fe_2O_3 + C = CO + 2FeO,$$

it was his (Mr. Yaneske's) opinion that the oxidation of the carbon was first effected by the Fe_2O_3 added (as ore) thus:

$$(1)\ Fe_2O_3 + C = CO + 2FeO.$$

The excess of FeO thus formed after satisfying the demands of the

SiO_2 of the slag was then reduced to metallic iron by a further oxidation of the carbon according to the equation :

$$(2)\ FeO + C = CO + Fe,$$

so that the reduction of Fe_2O_3 to Fe took place by two stages.

The fact that the authors found the Fe_2O_3 content of the slag was not raised immediately after the addition of Fe_2O_3 as ore, whilst the FeO was considerably increased, showed how rapidly Fe_2O_3 was reduced to FeO, while the further reduction of FeO by the carbon was not so rapid, as that oxide was much more stable in the slag and the demands of the silica had to be satisfied first before the excess FeO was reduced by the carbon. Percy's experiment to reduce a melt of fayalite composition by carbon failed for the reason that it is only free FeO (not combined with silica) which can be reduced by carbon. He (Mr. Yaneske) was of opinion that the equation given by the authors in which metallic iron was oxidised by its higher oxide, thus : $Fe_2O_3 + Fe = 3FeO$, took place simultaneously with the oxidation of the carbon by the Fe_2O_3 added as ore, and the FeO produced in excess of that required by the silica was then reduced by the carbon. In either case the oxidation of carbon by FeO was only a secondary reaction.

He thought gas oxidation was effected during the "boil" by direct contact of metal and gas owing to the agitation of the bath by the evolution of CO. When the carbon was low in the bath and the boil had almost subsided, he agreed with the authors' conclusions that gas oxidation might take place owing to the formation of Fe_2O_3 by the oxidising action of the gases on FeO of the slag, and the higher oxide formed being reduced to FeO again by the carbon. The occurrence of Fe_2O_3 in the slag would depend considerably upon the amount of FeO in the slag and carbon in the metal, and the oxidation of FeO by the action of the furnace gases would be prevented during the "boil" by the evolution of CO. As soon as the carbon was low in the bath, there was more likelihood of FeO being oxidised by the gases as the authors found. Limey slags containing less FeO would not become oxidised to such an extent, and therefore samples of such slags have a thinner oxidised layer.

Messrs. WHITELEY and HALLIMOND, in reply, agreed with Mr. Saniter that prior to the war too refractory sands were often used. Provided that the impurity present was chiefly alumina, sands containing 97–98 per cent. silica worked quite satisfactorily. In the instance referred to of a slag containing 25 per cent. of iron throughout the boil, the authors had been careful to state that that was an average analysis; when once the charge had settled down on the boil, the average quantity of iron in the slag remained fairly constant, if lime or other bases were not added with the ore in any quantity. Of course, the addition of ore raised the iron content for a time, but it gradually receded again to the average amount, which was conditioned by the degree of viscosity of the slag required by the smelter. If, as Mr. Saniter suggested, a great deal of oxidation occurred at an early stage, that would not affect the calculation of the relative amounts of ore- and gas-oxidation; the total oxygen added as ore was known, the total oxygen required by the metal was also known, and the difference must therefore be due to gas-oxidation. Dr. Rogers had remarked on the importance of minimising as much as possible the iron oxide in the acid bath before addition of deoxidisers. That could only be done by a correct regulation of the slag, and it was therefore very important to understand the reactions which took place. Dr. McCance's experiments on the increase in weight of acid slags through roasting in air were very interesting, and there could be no doubt that at high temperatures Fe_3O_4 was more stable than Fe_2O_3. The authors considered that the evidence at present available was quite insufficient to determine the state of combination of the iron in those melts. It was only necessary to recall the work done on aqueous solutions to realise how much further research would be required before it could be said definitely in what proportion the magnetite molecule was present. The crystallisation of the solid was in itself all but valueless as an indication of the proportion of molecules present in the liquid, and the authors had therefore preferred, in dealing with the reactions, to consider only FeO and Fe_2O_3. Why, however, did Dr. McCance stop there? If Fe_2O_3 was not to be mentioned, neither should FeO be, as in all probability it really existed as $2FeO,SiO_2$. The question was one which could not be ignored in dealing with the equilibrium between metal and slag. With regard to the question of gas-oxidation, Dr. McCance apparently contended that with a shallow bath in a quick working furnace the amount of gas-oxidation should increase. With that the authors could not agree, for it was obvious that, other things being equal, the faster the rate of working the less would be the amount of gas-oxidation. In shallow baths, owing to the enlarged area of contact, that action was to some extent counterbalanced by the greater speed at which oxygen was picked up, and the resulting proportion might be much the same as in a deep bath. So many factors entered into the question that comparisons of that sort might be very misleading. Dr. McCance held that 50 per cent. of the missing oxygen was abstracted from the metal. If that were actually the case, it would mean that at the beginning of the boil the metal would hold about 4 per cent. FeO in the presence of about 2 per cent. of carbon. If acid steel could hold that amount of FeO under the above conditions, one would expect at least as much to be present in Bessemer steel, but recent figures given by Oberhoffer (*Stahl und Eisen*, Feb. 7, 1918) showed that in no instance, before the addition of a deoxidiser to Bessemer steel, was 0·10 per cent. of oxygen present.

The authors were indebted to Dr. Stead for his very appreciative and encouraging remarks. The similarity between the structure of the roof-brick and the hearth to which Dr. Stead referred was very marked; the rigidity, at high temperatures, of structures containing so little solid silica was one of the most interesting and important features in the behaviour of that refractory.

It was very pleasing to find that Dr. Howe's views on the question of the part played by Fe_2O_3 in the slag so nearly coincide with those expressed in the paper. The action of even small amounts of Fe_2O_3 in refining operations did not seem to have received sufficient attention in the past. The authors would assure Dr. Howe that it was also good British practice in making high grade steels to avoid any darkening in the colour of the slag towards the finish; but for many purposes that was not essential, especially in making certain classes of mild steel. In such cases the darkening colour afforded the smelter a useful indication of the condition of the bath, particularly as regards its carbon content. As Dr. Howe pointed out, if a dark slag were present on tapping, final deoxidation must always be done by the addition of deoxidisers. The importance of controlling the Fe_2O_3 in the slag when best quality steel was to be made was thus evident.

The table given by Mr. Fletcher and the statement he made that when the silica content of puddling slags reached 40 per cent. the Fe_2O_3 disappeared, fully corroborate the authors' experiments on the action of silica on the equilibrium between FeO and Fe_2O_3. The similarity between the behaviour of CaO and MnO in puddling slags to which he also referred was of interest. The action of MnO in acid open-hearth slags still required much study; very probably it behaved in a manner similar to CaO.

Replying to Mr. Yaneske the authors were in doubt as to whether his explanation of the action of CaO in lowering the FeO content of the slag was based upon definite experimental evidence or merely upon opinion. If, as Mr. Yaneske stated, the CaO did not displace FeO until all silica in excess of the meta-silicate ratio had been satisfied, it would mean that no displacement of iron could occur until the silica content of the slag had been lowered to about 47 per cent. With that contention the authors were unable to agree, for they had found repeatedly that the addition of CaO to a slag containing even 55 per cent. silica caused a lowering of the FeO far in excess of that which would be due merely to dilution with CaO; in fact, the FeO content could be halved by CaO additions without increasing the viscosity and with a silica content maintained well above 50 per cent. The great loss of metal in the first charge on a new hearth referred to by Mr. Yaneske, no doubt, when oxidised, provided a considerable quantity of the FeO subsequently found in the hearth. Mr. Yaneske's statement that CO prevented the oxidation of FeO by the furnace gases required proof as it was certainly not the case in the basic process. Here as much as 1·5 per cent. Fe_2O_3 could be present in the slag during a vigorous boil, and if CO was so very active in reducing small quantities of Fe_2O_3 at those high temperatures, as Mr. Yaneske considered it to be, so high a content of Fe_2O_3 in a basic slag during a good boil would be impossible.

DEOXIDATION, AND THE INFLUENCE OF LIME ON EQUILIBRIUM IN THE ACID OPEN-HEARTH FURNACE.

By B. YANESKE (Sheffield).

INTRODUCTION.

There has recently been a great deal of controversy between steel-makers relating to the value of limestone in the working of a charge in the acid open-hearth furnace. At some steelworks it is the usual practice for the melters to add considerable quantities of limestone to the bath during the oreing period, whilst at other works limestone is seldom used owing to the view that it is not essential, or that it has an injurious effect on the quality of the steel. It is the author's experience that insufficient attention is paid by some steel-makers to the condition of the slag during the working of a charge. Their object being to make steel and not slag, the composition of the latter does not interest them, and they entirely overlook the fact that the quality of the steel depends upon the state of the slag.

The author's object in submitting this paper is to illustrate the utility of taking slag samples in conjunction with metal samples; to explain the effect which the addition of limestone[1] has on the slag and metal; and to point out how valuable limestone can be, if used judiciously, in obtaining perfect equilibrium in the furnace bath, which can only occur when the metal has become thoroughly deoxidised, the attainment of this condition being essential before the addition of the finishing alloys if the subsequent production of steel of the highest quality is desired. To explain how such a condition may be consistently acquired, it is necessary to describe the manner of working a charge, which the author has found to be ideal for the end in view.

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[1] The use of limestone in the acid open-hearth process has been previously referred to by Kilby, *Journal of the Iron and Steel Institute*, 1917, No. I. p. 76, and by Rogers, *ibid.*, 1917, No. II. p. 183.

THE PROMOTION OF EQUILIBRIUM BY THE USE OF LIMESTONE.

Taking as an example the working of a 0·50 per cent. carbon steel heat, the charge consisting of 50 per cent hæmatite pig iron (4 per cent. carbon, 2 per cent. silicon) and 50 per cent. scrap, the first point to be observed is the necessity of melting down very hot, which reduces the basicity of the slag formed by oxidation, &c., during the melting period, the proportion of silica to basic oxides composing the slag being a function of the temperature. When the charge is clear-melted, the addition of iron ore should never be commenced until the melter is certain that the bath is sufficiently hot.[1]

If at this stage a sample of slag be taken in a small test-spoon and the fracture examined, whether the sample has been quenched in water or allowed to cool in the air, it will be found to be black or bronze in colour, with a metallic appearance due to the high percentage of basic oxides (FeO and MnO) present, and the composition will be approximately—SiO_2 48 per cent., MnO 16 per cent. (depending upon the percentage of manganese in the charge), and FeO 33 per cent. The basicity of the slag depends upon the proportion of the total basic oxides to the acid silica, but as the percentage of MnO, once established, usually only changes by steadily decreasing as the volume of slag is necessarily increased by the additions of iron ore, it is therefore the proportion of FeO to SiO_2 (both of which are variable to a considerable extent according to the working of the charge), to which attention is chiefly directed.

When the temperature after melting is quite satisfactory, additions of iron ore can be made at a fairly rapid rate without risk of cutting the furnace hearth. The primary object being to obtain a high quality of steel as expeditiously as possible, the bath is quickly brought to the "boil" by continuous ore additions. It is essential that a highly siliceous slag be formed during the oreing period, and this can only be achieved by maintaining the bath at a high temperature throughout the whole operation. After the "boil" has been obtained, samples of slag are taken and fractured at intervals between periods of steady ore additions, and it is observed that as the SiO_2 increases and FeO consequently decreases in the slag, the fractures become lighter in colour. The steadily increasing acidity of the slag can also be discerned by the appearance of the "boil" in the furnace, for the slag becomes more and more viscous, whereas it is thin and mobile when the slag contains a high percentage of FeO.

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[1] Optical pyrometers are very useful for controlling furnace bath temperatures, and the premature addition of iron ore can be prevented if a satisfactory pyrometrical reading of the surface of the bath is obtained (while the gas is absent during the reversing period), before the addition of iron ore is commenced.

Spoon samples of metal are also taken periodically, and if a reasonable amount of "stewing" has been allowed after each ore addition, with the bath kept consistently at as high a temperature as the refractories of the furnace will allow, the samples will become more or less riddled with holes, and the slag covering the metal is seen to rise in the spoon owing to the escape of gas. This is a true indication that a stage has been reached when the slag has become so highly siliceous that there is an excess of SiO_2 above that required to satisfy the reduced amount of basic oxides present. Consequently this excess SiO_2, once free from combination with the basic oxides, begins to be reduced by the iron, the silicon passing into the metal, and the oxygen liberated from the SiO_2 perforating the metal samples, thus:

$$SiO_2 + Fe = FeSi + O_2$$

In the furnace bath, where the slag is only in contact with the surface of the molten metal, the oxygen will escape from the silica reduced without passing through the metal.

The author here ventures to disagree with several authorities [1] who have stated that it is the carbon which effects the reduction of the silica according to the equation:

$$SiO_2 + 2C = Si + 2CO$$

It is the author's opinion that iron must be a far more powerful reducing agent than carbon, for iron is always present in great excess, and it is an established fact that oxygen has a greater affinity for silicon than for carbon in the open-hearth furnace, this being the basis of the acid process, therefore it seems highly improbable that carbon will displace oxygen from combination with silicon at the furnace temperature. For carbon to reduce silica according to the preceding equation, it is easily calculated that there must be a loss of 0·06 per cent. carbon from the metal for each gain of 0·07 per cent. silicon from the slag, and yet analyses have proved to the author that the reduction of silica has frequently occurred to such an extent that the percentage of silicon passed into the metal from the slag has exceeded 0·10 per cent. whilst the carbon in the bath has not fallen more than 0·03 per cent. In fact, he has always found the loss of carbon to have been less than normal whenever there has been a considerable gain of silicon from the slag, for whatever be the true reaction it is obvious that for silica to be reduced at all, the amount of oxygen dissolved in the metal must have reached a minimum; therefore it can only be by atmospheric oxidation effected by the action of the furnace gases that the carbon is removed when the metal is free from dissolved FeO. Fe in the absence of dissolved oxygen is also liable to reduce some of the silica of the hearth, particularly when the hearth has been newly sanded, the silicon passed into the metal being again oxidised by the subsequent addition of iron ore, thus causing an increase in the silica content of the slag.

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[1] *E.g.* H. H. Campbell in "The Manufacture and Properties of Structural Steel," 1896 edition, p. 130, and J. E. Stead in his contribution to the discussion on "The Elimination of Silicon in the Acid Open-Hearth" by McWilliam and Hatfield, *Journal of the Iron and Steel Institute*, 1902, o. I. p. 73.

When, and not until, the reduction of silica occurs as indicated by the holes in the metal samples, limestone is carefully added with the next ore addition. The addition of limestone at this stage prevents the reduction of SiO_2 from the slag, as the CaO provides a new base for the excess SiO_2, the two compounds forming a lime silicate (CaO, SiO_2) in the slag. The iron ore (Fe_2O_3) directly attacks the carbon, whereas if the lime addition is omitted, so much of the oxide of iron will be required to oxidise the silicon passed into the metal, and to provide a base for the excess SiO_2 in the slag. After the addition of sufficient limestone the holes soon disappear from the metal samples, and the melter is enabled to obtain a sound sample, by the fracture of which he can more easily judge the carbon content of the metal. The addition of limestone also increases the fluidity of the slag, which would otherwise become too viscous with such a high silica content.

Each time that holes occur in the metal samples a little more limestone is added with the next ore addition, and the addition of ore can be fairly rapid whenever the holes appear in the samples, so long as the carbon in the metal is well above that at which it is desired to tap the furnace. The practice of some melters is to lower the temperature of the bath by turning off some of the gas for a short time whenever the samples become riddled with holes, or the slag becomes too viscous owing to a high silica content. The reduced temperature of the bath facilitates the oxidation of Fe from the metal, thus effecting an increase of FeO in the slag. This procedure, however, is very unsatisfactory, as it is not always possible for a melter to control the temperature of his furnace bath to such a fine point that just sufficient FeO is taken up by the slag to combine with the excess SiO_2, and the lowering of the temperature may easily be overdone to such an extent that the slag becomes highly basic with FeO, with its consequent undesirable results, whereas a melter can judge very accurately by practice how much limestone is required to " clear " his samples. The practice of varying the temperature also greatly endangers the life of the furnace.

The addition of cold scrap to the bath will also prevent the reduction of SiO_2 by lowering the temperature of the bath. Rogers[1] has referred to the use of scrap for obtaining a properly " dead-melted " condition when the metal has become over-oxidised by excessive temperature. The present author has never known the metal to become " wild " owing to the application of too much heat, and it is his opinion that most probably the samples " lifted " in the spoon owing to the reduction of SiO_2, this being mistaken for wildness. The addition of scrap, by chilling the bath, has caused the reaction to cease.

After the addition of limestone has been commenced, the presence of CaO can be discerned in the slag samples, the fractures showing a green coloration. This green colour is more pronounced in a slag which has been quenched in water than in one which has been allowed to cool in the air. As more and more limestone is added, the quenched slag assumes a light green colour, corresponding to a light greyish-green colour in the air-cooled sample. When these colorations have been obtained, the addition of limestone is discontinued and only iron ore added, for the presence of too much CaO would prevent any further reduction of SiO_2 from the slag, required at the end of the process. When it is judged by the fracture of the metal samples, or by carbon determinations, that the carbon content of the metal is nearing the percentage at which the finishing additions are to be made, the addition of iron ore is discontinued, and the bath is allowed to "stew," until the appearance of holes in the metal samples again shows that SiO_2 is being reduced from the slag at a little above the desired carbon percentage, when a final addition of limestone is cautiously made. Only just sufficient is added to provide the CaO necessary to combine with the excess SiO_2, the limestone being added a little at a time until perfect equilibrium between the slag and the metal is obtained.

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[1] *Journal of the Iron and Steel Institute*, 1917, No. II. p. 188.

The fracture of the quenched slag at the end of the process should be of a light green colour, with a sub-vitreous lustre, whilst the fracture of the air-cooled slag should be light greyish-green, with light green edges where the slag has cooled more rapidly than the interior, the air-cooled slag possessing a very tough stony texture. An analysis of the slag will be approximately:

SiO_2. Per Cent.	FeO. Per Cent.	CaO and MgO. Per Cent.	MnO. Per Cent.
58	21	5	12

For equilibrium to be obtained it is essential that the metal be thoroughly deoxidised, and all reaction between the slag and metal must cease. This condition is only indicated by the appearance of the metal samples, which show clearly the degree of deoxidation of the metal, for the slightest reaction occurring can be easily discerned by an examination of the upper surface of the samples, when no reaction is apparent in the test-spoon. When true equilibrium, or in other words an absolutely "dead-melted" condition of the bath, is acquired, the metal samples will be found to be perfectly sound in every detail, the limit of deoxidation of the metal having been reached when it is observed that the skin of the sample shows rippled marks on the upper surface, caused by the surface tension of the liquid metal. C. Johns[1] was the first to point out that this surface tension phenomenon is the most valuable indicator of the purity of the molten metal, for, as in other liquids, the degree of the surface tension is decreased by the presence of certain impurities, so these surface tension ripples never occur when any appreciable amount of FeO remains dissolved in the metal.

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[1] *Journal of the Iron and Steel Institute*, 1917, No. II. p. 194.

Although the metal must be in a highly deoxidised condition before equilibrium can be attained, yet it often occurs that whilst the metal is thoroughly deoxidised, equilibrium of the bath does not take place owing to the reduction of silica from the slag. Thus metal samples will be obtained showing surface tension ripples on the upper surface, and having deep holes in the under surface due to the pressure of the oxygen escaping from the SiO_2 upon reduction. The addition of a little limestone to the bath will soon cause the holes to disappear from the samples, and as soon as the samples become quite sound (whilst the skin of the upper surface is rippled) a perfectly "dead-melted" condition of the bath is obtained. Different stages of oxidation are clearly indicated on the upper surface of the metal samples. The nearest approach to the ideal sample showing surface tension ripples is one which is quite smooth on the upper surface. Then follows the sample which is slightly sunken, and shows signs of dendritic crystallisation due to a slight reaction taking place in the test-spoon. This class of sample is obtained when there is a little FeO present in the metal owing to slightly excessive limestone or ore additions. There are various qualities of samples below this category, but the examples given serve to illustrate the author's meaning.

By the foregoing procedure it is possible to obtain a perfectly "dead-melted" condition at any carbon content of the bath. As the attainment of equilibrium can only be temporary, as soon as this condition is obtained and the percentage of carbon in the bath is satisfactory, the usual finishing additions should therefore be made to the bath during the final carbon determination, and the furnace quickly tapped, and any further manganese, silicon, or anthracite coal additions made to the ladle after tapping.

A good casting temperature is ensured by this method, for the steel is always hot enough to cast if the bath is hot enough to cause the reduction of SiO_2 from the slag, whereas it is possible to obtain sound samples by "killing" an oxidised bath with additions of silicon or manganese (or both), even though the steel be too "cold" to cast.

The additions of limestone during the early stages of the operation as described, are only necessary when a good quality of hæmatite iron ore is used containing a low percentage (usually less than 1·5 per cent.) of CaO and MgO (which acts similarly to CaO). If an iron ore be used which contains a high percentage of CaO, such as some qualities of Spanish ores, the CaO of which may average over 6 per cent., the slag fractures very soon become green, as the ore itself adds sufficient lime to yield a green coloration. When it is seen that the slag is becoming light green with only ore additions, limestone should only be added at the end of the operation when holes appear in the metal samples after the final " stewing " of the bath.

When making nickel-chrome steels, nickel-chrome scrap having been charged, the same procedure as described for carbon steels is followed, but darker coloured slags are obtained owing to the presence of Cr_2O_3 in the slag.

THE EFFECT OF AN EXCESSIVE ADDITION OF LIME.

The addition of lime in excess is sometimes due to the fact that too much faith is placed in the application of the physico-chemical partition law which indicates that with a constant temperature the ratio of the concentration of FeO in the metal to the FeO in the slag is constant, and that therefore the lower the percentage of FeO in the slag, the lower the percentage of FeO in the metal. Limestone is therefore added in considerable quantities during the working of a charge with the object of steadily decreasing the concentration of FeO in the slag, so that by the end of the process the slag will contain a very low percentage of FeO, and a correspondingly low concentration of FeO in the metal is expected.

The addition of any CaO beyond that which may be required to satisfy any excess SiO_2 of the slag as previously described in the paper, results in the displacement of some FeO from the slag. The slag consists of a solution of (R)O silicates, the silica being divided between the bases according to the proportion in which they occur in the slag.[1] The further addition of the base CaO combines with its equivalent of SiO_2, which has a greater affinity for CaO than for FeO, due to the fact that the iron of the metal possesses a great tendency to dissolve its own oxide, whereas it is only possible for CaO to be dissolved into the slag. The FeO expelled from the slag passes into the metal, and equilibrium is not attained until this FeO is reduced by the carbon of the metal, thus[1]:

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[1] *Vide* C. Johns' contribution to the discussion on Rogers' paper, *Journal of the Iron and Steel Institute*, 1917, No. II. p. 193.

$$(2FeO, SiO_2) + CaO = (CaO, SiO_2) + 2FeO$$
$$FeO + C = Fe + CO$$

Whilst, then, it is preferable to replace some of the FeO by CaO, this should only be carried out to the extent of equilibrium being restored by the carbon of the metal reducing all the FeO displaced from the slag, before the percentage of carbon is reached at which it is desired to tap the furnace. If, therefore, a melter adds a little excess limestone beyond that required to clear his metal samples of holes during the early stages of the process, no harm ensues while the carbon in the bath is well up, but at the end of the process great care should be exercised that the limestone addition required is not exceeded.

When the metal samples at the end of the operation show the presence of a little dissolved FeO due either to slightly excessive limestone or ore additions, sound samples can soon be obtained if a little siliceous pig iron be allowed to melt on the banks of the hearth and run into the slag, but it is always preferable to avoid the necessity for this adjustment.

If limestone be incautiously added during the working of a charge, the slag may contain such a high percentage of CaO that it is very difficult, and sometimes impossible, to get it into such a condition that SiO_2 begins to be reduced, even after lengthy "stewing" of the bath, for the occurrence of this reaction is prevented, first, by the displacement of FeO from the slag into the metal, and secondly, by the demand of the excessive amount of CaO present for SiO_2 which it will obtain by attacking the furnace hearth at the slag level.

The presence of a high percentage of CaO in the slag can always be discerned by an examination of the slag fractures. At the end of the process described by the author, the slag obtained is light green with a sub-vitreous lustre for the quenched sample, and light greyish-green with a stony texture for the air-cooled sample, the percentage of CaO and MgO in the slag being about 5 per cent. When the percentage of these bases is in the proximity of 7 to 10 per cent. and the silica 55 to 58 per cent., both the quenched and air-cooled slag samples assume a bottle-green colour with a more vitreous lustre, and a slag containing about 10 per cent. CaO and 55 per cent. SiO_2 possesses the property of being drawn out, whilst molten, into threads like glass wool. Threads of such slag have been observed by the author to stretch from the furnace to the water-bosh, a distance of several feet, slag adhering to the test-spoon having been drawn out as the sampler has carried the spoon away from the furnace. Whenever it is observed that the air-cooled slag sample is green as well as the quenched sample, difficulty is usually experienced in obtaining the reduction of SiO_2 from the slag as desired by the author at the end of the process.

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[1] McCance has shown in his admirable paper on "Non-Metallic Inclusions in Steel," *Journal of the Iron and Steel Institute*, 1918, No. I. p. 266, that the iron most probably exists in the slag as fayalite ($2FeO, SiO_2$) and the manganese as rhodonite (MnO SiO_2).

Many cases are known to the author where such large amounts of limestone have been added to the bath, that, in addition to the CaO having seriously damaged the furnace banks, the FeO expelled from the slag has not nearly been reduced by the carbon of the bath, even after many hours " stewing " down to about 0·10 per cent. carbon without ore additions. In such cases, when samples of metal are taken from the bath, the slag in the spoon is seen to rise owing to the escape of CO from the metal, leaving a space between the slag and the upper surface of the metal, and the metal samples are badly " nibbled " round the sides and on the upper surface owing to the energetic reaction between the dissolved FeO and the carbon in the metal. These marks are easily distinguishable from the holes caused by the reduction of SiO_2, which always appear on the under surface of the sample first.

It may happen that the presence of such an excess of CaO in the slag is not entirely due to the addition of limestone, but to the use of an iron ore containing a very high percentage of CaO, such as 10 per cent. or over, or to the addition of basic slag in error which sometimes occurs in steelworks where both basic and acid furnaces are in operation.

If the bath be " stewed " for lengthy periods when there is an excessive amount of CaO present in the slag, it is possible to obtain a slag very high in SiO_2 and low in FeO, which according to some steel-makers is all that is desired, and yet the metal samples will be very poor, being badly "nibbled." When a sample of such slag containing both high percentages of CaO and SiO_2 (*e.g.* 10 per cent. CaO and 62 per cent. SiO_2) is taken and fractured, whether it has been air-cooled or quenched in water, it will be found to be very brittle, and to have a brown or yellow colour, with a vitreous lustre, in contrast with the bottle-green colour obtained with such a high percentage of CaO but a lower percentage of SiO_2, the fractured surface of the slag always being very shiny when there is a high percentage of CaO and MgO in the slag, and the lustre of the quenched slags is of a higher degree of intensity than the lustre of the air-cooled slags. Contrary to the statements of some writers that the continued addition of limestone consistently causes the slag to become more and more mobile, this is only true when the SiO_2 content of the slag does not exceed 58 per cent., for if 60 per cent. or more SiO_2 be present, a stage appears to have been reached when the slag loses its mobility no matter how much CaO is added. Kilby [1] has alluded to slags containing 60 to 62 per cent. SiO_2 and about 10 per cent. CaO as being in a fairly mobile condition, but it is the present author's experience that when a slag of such composition is obtained it is not at all mobile, but has a very pasty appearance in the furnace, and it is very difficult to establish equilibrium in the bath so as to obtain sound metal samples.

The following is an analysis of a very siliceous slag containing a high percentage of CaO, in the presence of which considerable difficulty was experienced in obtaining satisfactory metal samples:

	Per Cent.
SiO_2	61·40
FeO	19·00
MnO	7·00
CaO	9·30
MgO	0·86
Cr_2O_3	1·14
Al_2O_3	1·00

This slag was very pasty in the furnace, and the fracture was brownish-yellow, with a vitreous lustre. The metal samples were very badly "nibbled," and the melter had unsuccessfully attempted to get rid of the marks on his samples by allowing the bath to "stew" for a lengthy period without ore, the carbon in the bath being about 0·15 per cent. when the slag sample was taken for analysis. Good samples were eventually obtained by recarburising the bath with pig iron, but this of course occasioned a great loss of time, and the casting temperature of the steel was below normal owing to the very pasty nature of the slag.

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[1] *Journal of the Iron and Steel Institute*, 1917, No. I. p. 80.

In another instance when a pasty slag of similar composition was obtained, causing defective metal samples, instead of allowing the bath to "stew" down, good hæmatite iron ore was added in excess for the purpose of increasing the percentage of FeO in the slag by oxidation of the Fe of the bath, causing loss of Fe from the metal, thus increasing the volume of slag and therefore decreasing the percentage of SiO_2 and CaO in the slag. This was found to be a much better method of dealing with such a slag, for by this procedure it became very fluid. The metal was then recarburised with sufficient pig iron to reduce the excess of FeO in the metal, while the slag was sufficiently fluid after recarburisation to prevent any difficulty in obtaining the steel hot enough to ensure a good casting temperature. The following are analyses of the slag before and after the addition of excess iron ore, the carbon in the bath being about 0·65 per cent. and 0·08 per cent. respectively when the slag samples were taken:

	Pasty Slag. Per Cent.	Fluid Slag. Per Cent.
SiO_2	62·2	56·6
FeO	16·1	23·8
MnO	8·2	7·4
CaO	10·7	9·75

When adding limestone it should always be remembered that once CaO is established in the slag it cannot be removed, and when this base is present in excess it is only by increasing the volume of the slag that the percentage can be reduced. This can be effected by the addition of a considerable quantity of a good quality of acid slag containing a low percentage of CaO, but this procedure would cause the charge to become practically unworkable owing to the large volume of slag which would result.

When the samples are defective owing to excessive lime additions, sound samples can be temporarily obtained by "dosing" the bath with such deoxidisers as ferro-silicon or silico-manganese.

This expedient may give satisfactory results for some classes of steel, but the finished steel would most probably contain an appreciable amount of insoluble silicates as a result, which non-metallic impurities are very undesirable in steels required for special purposes. If the purpose for which the steel is required will allow such additions to be made the furnace should be tapped as soon as possible after the samples are satisfactory, before the slag has time to react, and any other additions of silicon and manganese required should be added to the ladle. Otherwise, it will not be long before the reaction of the slag causes the samples to become almost as bad as they were before the additions were made.

Whenever it is observed that the slag is very thin, *i.e.*, highly basic with FeO, owing to the furnace having been maintained at too low a temperature during melting or whilst oreing, it is foolish for a workman to add any limestone to the bath. When such a slag is obtained it will usually tax a melter's skill and patience to get rid of the great excess of dissolved FeO from the metal so as to get the bath into proper condition or equilibrium, without making matters worse by causing the slag to pass more FeO into the metal as a result of the addition of CaO to the slag. If the slag be still very thin at the end of the process, carbon, silicon, and manganese losses cannot be properly controlled, owing to the excessive amount of dissolved oxygen in the metal, and if the charge be tapped under such conditions and normal finishing additions made either to the furnace bath or in the ladle, the percentage of these elements will be found to be low in the " pit " sample, and if the silicon be very low " blowholes " may result in the ingots.

When a very mobile slag highly basic with FeO is obtained and there is insufficient carbon in the bath to effect the reduction of the excess FeO present in the slag and metal, equilibrium can only be acquired by recarburising the bath with sufficient hæmatite pig iron to reduce the excess FeO, both the carbon and silicon of the pig iron being available for this purpose. The advisability of working the furnace at as high a temperature as the refractories will withstand, during both melting and oreing periods, cannot be too greatly emphasised, as by this means the occurrence of such an undesirable slag is obviated.

The presence of an excess of lime in the slag may sometimes be due to the melter having attempted to thin a " dirty " slag, caused by patches of sand from the furnace hearth, or by the refractory bricks of the furnace having fused and run into the bath owing to the furnace having been worked at an excessive temperature. The employment of limestone for such a purpose is useless, for the lime only combines with the slag proper, and has no effect on the foreign siliceous matter which rests on the surface of the real slag. Instead of adding limestone, the slag should be cleaned by the workmen raking off as much of the siliceous matter as possible.

Conclusion.

Whilst the author admits that for certain classes of steel such as that required for ship and similar plates, it is unnecessary to obtain a very highly deoxidised bath, yet for special steels (particularly nickel-chrome) which have to undergo severe mechanical tests, forging and machining operations, it is really essential that such a condition of the bath be obtained before the finishing alloys are added.

One of the chief causes of flaws observed in the manufacture of certain steel articles is the presence in the steel of segregations of non-metallic inclusions, the majority of which consist of a mixture of silicates of iron and manganese (often with manganese sulphide) in solution. These silicates are chiefly formed by the addition of the deoxidisers silicon and manganese to a steel containing an appreciable quantity of dissolved oxygen as FeO[1] (and CO), hence the desirability of procuring a well deoxidised bath before the addition of the deoxidising alloys, instead of relying on the addition of the alloys to effect deoxidation.

It is comparatively easy to control silicon by the judicious use of limestone as described in the paper. If, instead of adding limestone to obtain equilibrium, the furnace be tapped whilst the metal samples are showing holes, and the normal silicon additions are made, the percentage of silicon in the finished steel will be found to be high. The proof is here furnished that silicon at this stage is being abstracted from the silica of the slag, for when holes appear in the metal samples it often occurs that much more silicon is found in the finished steel than is known to have been added, after allowing for the usual residual silicon in the metal.

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[1] The hypothesis that dissolved FeO was the main cause of the formation of these inclusions was first propounded by C. Johns, *Journal of the Society of Chemical Industry*, April 30, 1918, and later corroborated by McCance, *Journal of the Iron and Steel Institute*, 1918, No. I. p. 284.

By consistently obtaining the same high degree of deoxidation with perfect equilibrium in the bath at the end of the process described by the author, there is always a minimum oxidation loss from the finishing alloys, and the analyses of the finished steels are consequently more constant than if varying oxidised conditions of the bath are successively obtained as in many methods of working, and deoxidisers then relied upon to remove the varying excess of dissolved oxygen. The loss of manganese and silicon in the ladle measures the degree of oxidation of the metal when tapped, and if a great excess of dissolved oxygen be present, then it may never be satisfied by the deoxidising elements. The resultant percentage of manganese and silicon in the finished steel will be very low, and the ingots will consequently contain "blowholes." The addition of aluminium is not required if the bath has been properly "dead-melted," for this deoxidiser can only replace FeO by forming infusible particles of alumina (Al_2O_3).

It is a well-known fact that the lower the carbon in the bath, the more oxygen is liable to be dissolved in the metal, as the carbon has less influence in removing it. As a result, there is usually more loss on manganese and silicon additions to the ladle, with a low carbon bath (say 0·10 per cent. carbon), than with a fairly high one (say 0·50 per cent. carbon), and it is also more difficult to effect the reduction of SiO_2 from the slag when the bath is low in carbon, as this reaction cannot take place when dissolved FeO is present in the metal. Therefore it is not advisable to allow the bath carbon to become much lower than is rendered necessary by the percentage of carbon required in the finished steel, of course allowing for the carbon added by the finishing alloys.

The metal, however, can be obtained in a perfectly "dead-melted" condition at 0·10 to 0·15 per cent. carbon quite successfully, if the bath be allowed sufficient "stewing" after the last ore addition to cause holes to appear in the samples, when a very cautious addition of limestone can be made quite safely, just sufficient being added to obtain perfectly sound metal samples.

The practice of taking the bath down to a low carbon content and then recarburising with pig iron, is a mere waste of time, unless the presence of a highly basic slag or other unforeseen circumstances have rendered this procedure necessary, for even though a "dead-melted" condition was obtained before "pigging-back," equilibrium relations between the slag and the metal require readjustment after the pig iron addition. When it has been found necessary to recarburise with pig iron and the bath was in proper condition previously, equilibrium is best restored by the addition of limestone to provide a base for the increased SiO_2 content of the slag, thus preventing the reduction of silica from the slag which would otherwise occur. If a lower percentage of silicon be required in the finished steel than is expected from the pig iron addition, the addition of sufficient excess limestone is essential to keep down the silicon in the steel after recarburisation. The FeO displaced (by the excess CaO added) from the slag into the metal containing a considerable percentage of silicon, will oxidise some of the silicon from the metal in preference to carbon until the bath is in equilibrium, and by this means the percentage of silicon in the metal will be reduced, thus:

$$2FeO + Si = 2Fe + SiO_2.$$

CORRESPONDENCE.

Dr. F. **Rogers** (Sheffield) wrote that he agreed in general respects with the author's discussion of the behaviour of lime in the acid slag, but possibly there were differences in some details, as, for example, in regard to the argument that—"If a melter adds a little excess limestone beyond that required to clear his metal samples of holes during the early stages of the process, no harm ensues while the carbon in the bath is well up, but at the end of the process great care should be exercised that the limestone addition required is not exceeded." He (Dr. Rogers) considered that there was no general occasion to add lime to clear the sample in the early stages, and that a great latitude was permissible in the late lime addition (if any). The author appeared to have in contemplation "holding" the carbon—a condition liable to be accompanied by coldness—or else dead melting at a previously selected carbon content, rather than in accordance with actual condition. Perhaps the author was not allowing nearly enough for the influence of temperature, as was apparent, for example, on page 261, and again in the remark on page 262 constituting the first paragraph of the section on "The effect of an excessive addition of lime," a remark which the author did not justify, owing partly to his ignoring the fundamental influence of temperature in that particular question of the equilibrium. Metallurgists were fairly agreed as to the reduction of silicon, established in McWilliam and Hatfield's paper, but he hoped presently to return to certain aspects of that subject. His criticisms would not, he hoped, detract from his appreciation of Mr. Yaneske's paper.

Mr. **Yaneske** wrote thanking Dr. Rogers for his interesting remarks. The object of adding limestone in the manner described was not specifically to clear the metal samples of holes. Limestone should never be added until those holes occurred in the samples. They indicated that silica was being reduced from the slag, so that by the addition of lime a base was provided for the excess silica, and more oxide of iron was available from the subsequent iron ore additions to oxidise the metalloids, instead of being partly used up in providing the FeO demanded by the excess SiO_2 in the slag. The slag was thus prevented from taking up too much FeO, CaO being substituted for the former base. The clearing of the samples after the lime additions was an indication that just sufficient lime had been added to effect the desired object, and at the same time the melter had a much better idea of what the carbon percentage was by the fracture of a solid sample than in the case of a perforated sample by which he was liable to be misled.

If a highly deoxidised bath were required, as in the manufacture of special steels, it was essential that the slag should be highly siliceous and contain a low percentage FeO. It was so easy to spoil the steel in attempting to obtain a low FeO content in the finishing slag by the incautious addition of lime that the use of that base should be under perfect control, and he did not agree with Dr. Rogers that a great latitude was permissible in the late lime additions, as the FeO displaced from the slag by the addition of excess lime had to be reduced by the carbon before the metal could be obtained as free as possible from dissolved FeO. Therefore if insufficient carbon were present in the metal to effect complete reduction by the time the furnace was tapped, the FeO still present in the metal could only be reduced by the deoxidising elements in the finishing alloys, that being the chief cause of silicate inclusions which were very undesirable in high grade steels required for certain purposes.

With regard to Dr. Rogers' remarks on the influence of temperature on equilibrium conditions, he (Mr. Yaneske) would remind him that the text of his paper was based upon the influence of lime on equilibrium, the temperature being maintained practically constant. The fact that the attainment of equilibrium was dependent primarily upon the temperature had been kept in mind throughout the paper, for he had repeatedly emphasised the necessity of working the furnace at a consistently high temperature during the process. Both the temperature and equilibrium conditions were always indicated by the appearance of the slag in the furnace and of the slag and metal samples. The occurrence of holes in the metal samples indicated the maximum temperature required for the process, for those holes never occurred when the bath was below the temperature required to produce a highly siliceous slag and to cause the subsequent reduction of silica. If the temperature of the bath were below that required to work the process in the manner described, lime would not be used, so that the question of the influence of temperature had no bearing on the discussion in which the influence of lime on equilibrium was considered. He looked forward with interest to the result of Dr. Rogers' intended investigations on the reduction of silica.

MACRO-ETCHING AND MACRO-PRINTING.[1]

BY J. C. W. HUMFREY, B.A., M.SC., M.ENG. (SHEFFIELD).

IN carrying out investigations upon specimens of steel, with a view to determining either their suitability for any given purpose, or the causes which have led to their failure in use, a knowledge of the macrostructure is usually as essential as a knowledge of the microstructure. The two are complementary, the former affording information as to the history in the ingot mould and during forging, while the latter affords information as to thermal treatment and composition, and at the same time enables the details of the macrostructure to be correctly interpreted.

The macrostructure of a cast metal is essentially due to segregation whilst solidifying; and it is convenient to consider such segregation to be of two kinds, which may be termed major and minor. Both are the result of the well-known phase law governing the solidification of a mixture of two or more mutually soluble constituents, which states that the first portions to solidify contain an excess proportion of the constituent having the higher freezing temperature, while the last portions to solidify contain an excess of the constituents having the lower freezing temperature.

Minor segregation is due to differences in composition which result between the portions of any individual crystal growing in the mass, and is an unavoidable consequence of the above-mentioned law. By regulating the rate of cooling through the solidification range, the number of centres from which crystallisation starts, and hence the individual crystal size, may be largely modified. Each individual crystal, however, always tends to form with a gradual variation in composition from nucleus to boundary. Thus whilst minor segregation may result in a structure which is macroscopic or microscopic, it can never be completely eliminated at the casting stage.

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[1] The subject-matter of this paper was to have been presented to the Institute at the May Meeting, 1917, but was withheld by order of the Admiralty until the conclusion of hostilities. In the meantime it has been communicated confidentially to several firms engaged in the manufacture of munitions.

Major segregation is due to the difficulty of ensuring that solidification shall proceed simultaneously from centres regularly distributed throughout the mass, and hence that the average composition of each crystal shall be the same. In practice the heat from the fluid metal has to be removed by conduction through, and radiation from, the walls of the mould ; and thus crystallisation starts from these walls, and may be complete in places adjoining them, before it has even commenced in places removed from them. Aggregates of crystals may therefore be formed during the early stages of solidification having an average composition quite different from that of other aggregates formed at later stages. The phenomena of major segregation are further complicated by the shrinkage which takes place on solidification, and by the evolution of gases.

Three of the elements present in plain carbon steels are known to be especially liable to segregate—viz. carbon, phosphorus, and sulphur ; the phenomena accompanying the segregation are, however, essentially different in the three cases.

Carbon and phosphorus are both soluble in molten iron as carbide and phosphide respectively ; and, if below certain percentages, are, on solidification, still retained in the form of solid solution. The first portions of the steel to solidify contain a lower percentage of both elements than the average, while the last portions contain a higher percentage.

After solidification is complete there is a range of temperature down to Ar1, in which carbide is readily able to diffuse. As a result of this diffusion, unless the rate of cooling is particularly rapid, the minor segregates of carbon formed on solidification (*i.e.* those occurring between different portions of individual crystals) are more or less obliterated. During the critical range an entire recrystallisation takes place, the carbide is finally thrown out of solution, and the individuality of the crystals formed on solidification is entirely lost.

Iron phosphide, on the contrary, appears to have a very slow rate of diffusion, except at temperatures just below those of complete solidification ; the segregates of phosphide, whether major or minor, appear to remain *in situ*, not only during the original cooling, but during all subsequent heatings and coolings, unless the temperature attained is but little short of that of incipient fusion. During the critical range, when the solid solution of carbide is separating into its constituents, it would appear that the carbide tends to concentrate in the areas low in phosphorus, which originally also contained least carbide, and thus partially to reverse the segregations of carbide formed on solidification: the action is, however, prevented by quick cooling through the critical range. The segregates of phosphorus are not affected by the recrystallisation during the critical range, and remain as pseudomorphs of the original dendritic crystals formed on solidification.

Sulphur, in the presence of sufficient manganese, is found in steel in the form of pale grey-coloured globules, which consist largely, if not completely, of sulphide of manganese. Evidence at present available points to the conclusion that this sulphide is insoluble both in solid steel, and at least for a certain range above the melting point of steel. It would thus appear that the segregation of sulphur in commercial steels—*i.e.* those containing sufficient manganese to prevent the occurrence of iron sulphide—is due to these globules being mechanically pushed to one side by the growing crystals, and concentrating in the last portions to solidify. Some become entrapped between adjacent dendritic arms and are thus finally found within the minor segregates, while others may escape to a later stage and swell the final concentration of impurities in the last portion to solidify—*i.e.* the major segregates. Thus, while the segregations of sulphur are usually identical with those of other impurities which are retained during solidification as solid solutions, it is owing to mechanical rather than to physico-chemical reasons that such segregation occurs. Owing to its insolubility in the steel it is obvious that the manganese sulphide will have no tendency to diffuse through the steel at any temperatures below that of incipient fusion.

Two methods are available for revealing the macrostructure of steel—viz. sulphur printing and etching.

Sulphur printing, carried out either according to the original method described by Heyn and Bauer upon silk, or according to the more generally used method of Baumann, with the aid of ordinary silver bromide paper, is of very great use in studying the extent and position of the major segregates. Its capability of revealing the minor segregates, and therefore of giving information as to the individual crystals existing in the original ingot immediately after solidification, is, however, somewhat limited for the following reasons:

(1) Unless the sulphur content be high, the globules of sulphide are too widely scattered to map out a clear continuous picture of the dendritic interspaces.

(2) Very great care is necessary to avoid even the slightest movement of the paper while in contact with the specimen, and also to ensure that the contact shall be uniformly close.

Provided, however, that the sulphur content be high, and that all movements be avoided, a very fair picture of the original dendritic crystals can be obtained.

Macro-etching is usually carried out with the aid of one of the following solutions:

(*a*) Solutions of nitric acid in either water or alcohol. This reagent is particularly useful for revealing the presence of fine flaws or cracks. These are best observed if, after fairly deep etching, the surface is wiped clean from all carbonaceous deposit and carefully dried with alcohol. The slight oozing which occurs from the flaws shows them in marked contrast to the general grey surface. To a certain extent this reagent brings out the major segregates, but is far more delicate in revealing carbon segregation, and especially any locally decarburised areas, than it is of revealing segregates of phosphorus and sulphur. The contrasts in this respect are best seen while the acid is still attacking the surface.

Except in the case of certain alloy steels, which appear to contain immobile carbides, the reagent is not sufficiently delicate to reveal the minor segregates.

(*b*) *Heyn's reagent* (12 per cent. solution of copper ammonium chloride in water) etches on the whole in a similar manner to (*a*), but at the same time tends to stain the portions high in phosphorus to a brown colour. This staining is not, however, sufficiently delicate to reveal the minor segregations of phosphorus.

(*c*) Strong (10–20 per cent.) aqueous solutions of hydrochloric acid or sulphuric acid, usually employed hot. These appear to act by firstly eating out the sulphide inclusions, and subsequently by acting upon the larger surfaces exposed to attack where the inclusions occurred, by eating out the segregates as a whole, and leaving the purer portions in relief. The general effect closely follows that obtained by sulphur printing.

(*d*) *Acid Cupric Reagents.*—These reagents have been described by Rosenhain and Haughton,(1) by Stead,(2) by Le Chatelier,(3) and by others. The solutions act by their power of differential attack on portions high or low in dissolved impurities, the attack being accompanied by a corresponding deposition of an adherent film of copper upon the surface of the steel. It is by means of this deposit of copper that the etching effects are judged. The reagents are remarkably sensitive, and are capable of revealing extremely small differences of composition such as occur between the various portions of a single original crystal. For the effects to be seen in the most favourable contrast the surface of the specimen requires to be given a fine polish such as given for micro work.

The reproduction of the results of any of the above methods of etching can only conveniently be done by photography; in the case of large specimens (*e.g.* complete sections of ingots) the reduction in size which this involves is liable to mask the finer details of the etching—upon which a great deal of the usefulness may depend. In the course of an investigation into the flow of the steel during the process of punching and drawing a shell blank, the author was successful in finding an etching reagent which, while having the delicacy of these mentioned under (*d*) above, could yet be applied to surfaces with an emery-paper finish only, and which allowed any number of exact full-size replicas of the etching effects to be obtained by a simple process of printing.

The solution is prepared by the addition of hydrochloric acid to Heyn's reagent, the most satisfactory composition for general use being:

Copper ammonium chloride	120 grammes
Hydrochloric acid (conc.)	50 c.c.
Water	1000 c.c.

The exact proportion of HCl appears to vary somewhat for different steels, but is easily determined by trial.

The etching is preferably carried out by supporting the specimen with the surface to be etched horizontal, and pouring on the solution at frequent intervals, so that a film of fresh solution is always in action.

The result of the etching is to produce a marked relief effect on the surface of the specimen, upon which the portions which solidified first are eaten out to a greater depth than the portions which solidified last; this relief effect is best seen after removal of the deposited copper. The addition of the hydrochloric acid causes the copper deposit to form as a continuous and somewhat adherent film, rather than as the loose flocculent mass left by the neutral solution. In the earlier experiments difficulty was frequently experienced in removing the deposit mechanically, and trials were made with various decoppering solutions to remove it chemically. Mr. Wesley Austin, who was then working with the author, found, however, that if the following procedure were adopted, the deposit could invariably be wiped away as easily as with the neutral reagent.

The etching is started with the neutral solution and is preferably continued with it until all traces of the scratches left by the emery-papers have been eaten away. To judge this it is necessary to wash off the deposit and examine the dried surface. When satisfactory in this respect the etch is again started with sufficient neutral reagent to form a complete but thin covering of the flocculent deposit, and then, in successive applications, the acidity of the solution is gradually increased up to the maximum. The attack is continued with this for about a quarter of an hour. The surface can be wiped free from copper at any stage and the effects of the etch examined, but after doing so the fresh attack should always be started with a preliminary application of the neutral reagent.

As stated above, the most favourable percentage of acid appears to vary somewhat for different steels. If insufficient is present, the relief effects are produced only slowly, and at the expense of a deep general attack upon the surface as a whole: if, on the contrary, the solution is too acid, there appears to be a somewhat vigorous attack upon the sulphide inclusions, which results in a deep pitting of the surface and a general spoiling of the whole effect. Alloy steels (*e.g.* nickel-chrome steels) appear to etch better with solutions of weaker acidity than do plain carbon steels, indeed quite marked relief effects can occasionally be obtained on the former with the neutral solution alone. File- or machine-marks should always be carefully removed by rough polishing before starting to etch, since the general effect of the acid solution appears to be to deepen rather than eliminate them. If the surface has been prepared by machine grinding, it should be finally polished by hand, or deeply etched with the neutral reagent, until all signs of surface hardening are removed.

After wiping away the deposited copper, and drying, the surface has a general matt-grey appearance upon which the relief does not stand out very distinctly ; if, however, it is lightly rubbed over with fine emery-paper, the relief portions are brought out into strong contrast, and the results of the etch are clearly revealed.

The total time taken to produce a satisfactory relief effect varies from about twenty minutes to one hour.

PRINTING.

The strong relief effects produced by the use of the acid solution suggested, at an early stage of the experiments, the possibility of reproducing the details of the etched surfaces by direct contact printing—*i.e.* by means of printer's ink and a press. The illustrations of macro-etchings which accompany this paper have all been so reproduced, the actual specimens being supplied to the printer. Apart, however, from the expensive printing machinery which has been used to obtain such prints in quantity, it has been found a perfectly simple matter to obtain equally satisfactory prints with apparatus readily obtainable in any laboratory or office.

It may be noted that there are two ways by which such an etched surface may be printed—viz. (1) in which the hollows are filled with ink and the reliefs wiped clean—this is the process used for copper engravings ; and (2) in which the reliefs are inked by means of a roller and the hollows left free. For simplicity, speed, and general convenience the latter process is much to be preferred ; and, after a few laborious trials of the former, has been entirely adopted. It is convenient also, since it reveals the segregates as dark, on a light background of the purer portions, and the prints are thus directly comparable with those obtained by sulphur printing.

The process of obtaining prints in the laboratory is as follows. The specimens are, when possible, machined into the form of slabs before etching, one of the parallel faces being that selected for etching. When a satisfactory etch has been obtained, ordinary printers' ink is applied to the surface by means of a roller. This is preferably of the type used by printers (covered by a special composition of glue and treacle), but results almost as satisfactory have been obtained with a roller made in the laboratory by covering a piece of iron rod with a length of thick pressure tubing, stretching two thicknesses of black para tubing over it, and mounting in an old squeegee handle. A few dabs of printing ink are placed on a sheet of glass or tin plate, and the roller passed in all directions over the sheet until the ink is evenly spread out. Ink is transferred to the specimen by passing the roller alternately over the inked plate and the etched surface. The specimen is then placed face upwards on the base of an ordinary copying-press, the paper laid upon it, covered with a pad, and pressure applied. The best results are usually obtained upon what is known as "glossy art paper," while for general use the best form of pad is two thicknesses of blue "livery" cloth, such as is frequently used for covering polishing discs. For specimens upon which a very deep relief effect cannot be conveniently obtained, better prints can often be secured by the use of a somewhat harder pad, *e.g.* a copy of one of the weekly technical journals.

For printing specimens too large for a copying-press, the paper may be pressed in contact with a heavy roller. Perfectly satisfactory prints have been obtained in this manner from the complete longitudinal section of a 1-ton ingot.

INTERPRETATION OF THE ETCHINGS.

Etched sections from unforged ingots appear to indicate, without any possibility of doubt, that the solution acts by attacking the purer portions which solidified first, with greater vigour than it does the more impure portions which solidified later. Etched sections from forged and treated specimens indicate with equal certainty that while the areas so differentiated may be deformed by the former process until the original dendritic pattern is rendered unrecognisable, yet the areas tend to retain their individuality in spite of any ordinary heat treatments, except such as are of abnormally prolonged duration, or are carried to temperatures approaching that of incipient fusion.

During the course of the last three years many specimens from all types of steel used in the construction of guns and shells have been etched in the author's laboratory, and only in those cases in which the microscope has given positive evidence of such incipient fusion or burning ([4]) has there been any failure to reveal the casting structure or to obtain satisfactory prints by the methods described.

The author has not yet had the opportunity of studying the recent publications of Le Chatelier, in which experiments have been described indicating that oxygen or oxide is the chief impurity, the segregation of which is responsible for the effects obtained with acid cupric reagents. It is considered, however, that the evidence ([2, 5]) which had been obtained previous to these researches points very strongly to phosphorus as the most important of these impurities, and that such evidence cannot be put to one side without very definite experimental data to the contrary.

In view of this belief in the importance of phosphorus in mapping out the dendritic structures of steel, the author has been in the habit of referring to the prints as "phosphorus prints." It is, perhaps, inadvisable to do so until further experimental data are available, and the less controversial name of "macro-prints" or "macrographs" is suggested instead.

The method of etching described in the present paper has suggested a method of attacking this problem, which should be capable of giving conclusive evidence. Only one experiment on these lines has so far been carried out. This experiment was as follows. A slab of steel showing a well-marked dendritic structure was etched to a deep relief. The relief portions were then very carefully scraped away from the surface and the scrapings collected. The surface was then re-faced, and the process of etching and scraping continued until sufficient scrapings had been secured to provide material for analysis.

Analysis of drillings from the slab showed that the average composition was—

	Per Cent.
Carbon	0·51
Silicon	0·13
Manganese	0·70
Phosphorus	0·040
Sulphur	0·041

whilst duplicate analyses of the scrapings gave 0·046 of phosphorus, and silicon and manganese the same as in the average drillings.

It is hoped, when opportunity offers, to continue experiments on these lines.

EXAMPLES.

The following examples have been selected from a number of cases which the author has dealt with in the course of investigations into steel for use in the manufacture of ordnance. They illustrate certain different applications of the method, and some deductions which may be made from its use.

Case I.—Prints 1 and 3 are from longitudinal axial sections of two small ingots intended for forging direct into shell blanks; prints 2 and 4 are from cross-sections of the same ingots, cut just at the top of the longitudinal sections. In both cases a certain amount of discard had been cut from the tops of the ingots before they were received for examination.

Ingot A (prints 1 and 2) was of circular cross-section, and, apart from some blowholes on the cut surface at the top (which, however, did not reappear on cutting off the cross slice), appeared generally to be sound. The external surface was fairly smooth and satisfactory (see Plate IX., Fig. 1).

Ingot B (prints 3 and 4) was of octagonal section, and, while the cut face appeared sound, the external surface was exceedingly rough and broken (see Plate IX., Fig. 2).

The compositions were:

	Ingot A. Per Cent.	Ingot B. Per Cent.
Carbon	0·58	0·56
Silicon	0·19	0·29
Manganese	0·68	0·73
Phosphorus	0·055	0·067
Sulphur	0·036	0·053

the drillings in both cases being taken from the top cut face at a point half-way between centre and outside.

Sulphur prints from the sections indicated no important major segregates, whilst etching with nitric acid only brought out a few hair-like shrinkage cracks in the central portions.

The macro-prints show very clearly the manner in which the steel has crystallised in the ingot moulds. As regards the length of the crystals which have grown inwards from the walls, and the shape and distribution of the equiaxial crystals which have formed within, the two ingots are fairly similar to one another, and suggest that in both cases the steel was poured at a low rather than at a high temperature. There is, however, one noticeable difference. In the prints from ingot B it will be seen that there is a sharply defined white line running roughly parallel to the exterior surface and at a distance of about ⅛ inch to ⅜ inch from it. Round the base of the ingot a series of such lines are evident. The space between this line and the surface was clearly mapped out in the sulphur print, in which it appeared as an evenly light tinted border, containing segregates of the blow-hole type. In the prints from ingot A the appearance is absent except for slight indications round the base.

Closer detail of the dendritic structure within the skin are shown in Plate X., Fig. 3, which is a photograph of the etched surface near the base of ingot B magnified four times.

The author considers that this skin has been formed owing to violent agitation of the liquid steel in the mould (probably due to too rapid pouring), successive skins being formed above the general level of the molten steel. When once the skins have become submerged crystallisation proceeds in the usual manner.

Case II.—Print 5 is from a cross-section of a segregated and unsound bar having the following general composition:

	Per Cent.
Carbon	0·45
Silicon	0·225
Manganese	0·76
Phosphorus	0·021
Sulphur	0·021

It is shown for comparison with the sulphur print (Plate X., Fig. 4) from the same section. It will be seen that the major segregates are revealed in a practically identical manner by the two methods.

Case III.—Prints 6 and 7 illustrate the use of macro-printing and etching in studying the flow of metal during forging. They are from longitudinal axial sections of the base portions of two shell blanks. In the case of the blank shown in print 6 the punch used in forging had a flat face, and it will be seen that the flow has taken place in such a manner as to produce a curious "cone" formation just beneath the base of the cavity. The manner in which this cone appears to be formed can be best explained by reference to the diagrams shown in Fig. 5. "A" represents a section of the blank before punching, upon which have been drawn a series of imaginary lines parallel to the axis. "B" represents the same billet after punching with a flat-nosed punch, and shows how these lines become displaced. A conical piece of steel from the top of the billet is pushed right down in front of the punch, practically without deformation; just beneath this undeformed portion the amount of lateral deformation suddenly rises to a maximum, so that a narrow axial cylinder in the billet is spread out to practically the full diameter of the punch. Below this maximum the lateral spread gradually becomes less, until at the base of the blank is again almost nil. In order to make the diagram somewhat clearer a central section has been cross-hatched in each figure.

In print 7 the punch had been given a bluntly pointed nose (corresponding approximately to the outline of the cone in print 6), and it will be seen that the cone formation is now entirely absent, and the steel has spread out regularly before the advance of the punch.

These differences have been found to have a very important bearing in practice. In a completely sound billet the cone formation is probably unharmful, yet if the billet has any original axial unsoundness (*e.g.* a minute pipe), a certain axial length of the defect becomes spread out so as to form a thin shell enclosing the cone, and the latter will then be only incompletely adherent to the base of the shell. One may compare the shape of a narrow axial cylinder in the billet before and after punching to a closed and open umbrella.

Many cases of such loose cones have been met with, the defect being particularly troublesome owing to the difficulties in detecting its presence. The fine junction of cone and base might be almost invisible when examining the machined interior of the shell, but if the base was struck a blow with a hammer the cone would fall right out into the cavity.

It is of interest to note that from some tests, the results of which were kindly shown to the author by Mr. James Waite, it would appear that the pressure required to punch a billet with the form of punch shown in print 7 is almost twice that required with the form shown in print 6. This indicates that the surface friction between hot steel and cold punch is considerably greater than the combined resistance of the slip surfaces in the hot steel.

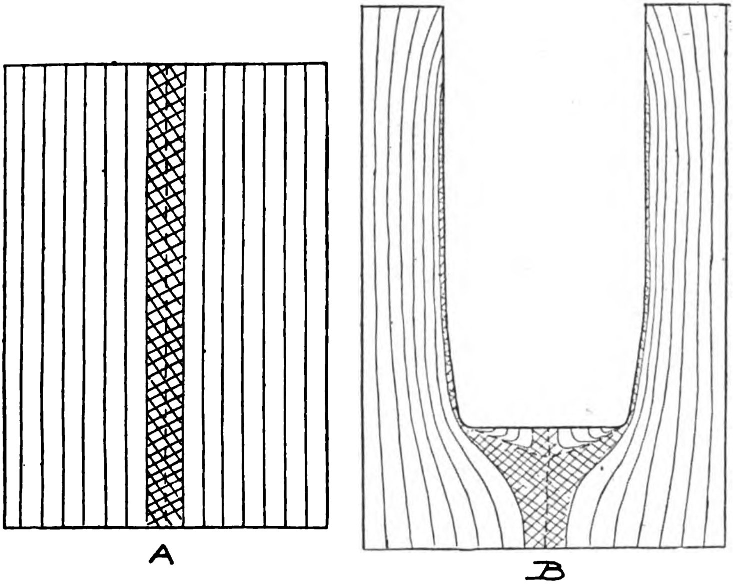

FIG. 5.—"Cone" Formation produced during Forging.

In conclusion, the author would like to express his thanks to his late assistant, Mr. Wesley Austin, M.Sc., for very valuable help in working out the practical details of the method, and to Mr. James Waite, M.B.E., who brought the problem illustrated in Case III. to his notice, this being, as mentioned above, the original starting point of the research.

The illustrations to the paper were all taken in connection with investigations carried out for the Director of Inspection of Steel (Land Service), who has kindly given permission for their publication.

REFERENCES.

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2. Stead, *ibid.*, 1915, No. I. p. 140.
3. Le Chatelier, correspondence on 2, *ibid.*, 1915, No. I. p. 196.
4. Stead, *ibid.*, 1915, No. I. p. 398.
5. Stead, *ibid.*, 1918, No I. p. 389.

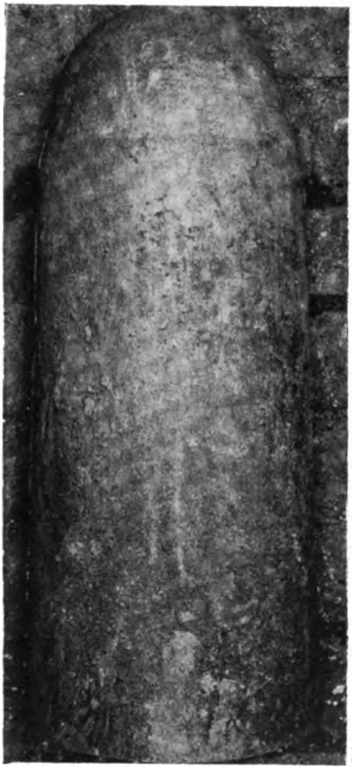

Fig. 1.—Surface of ingot A (page 282).

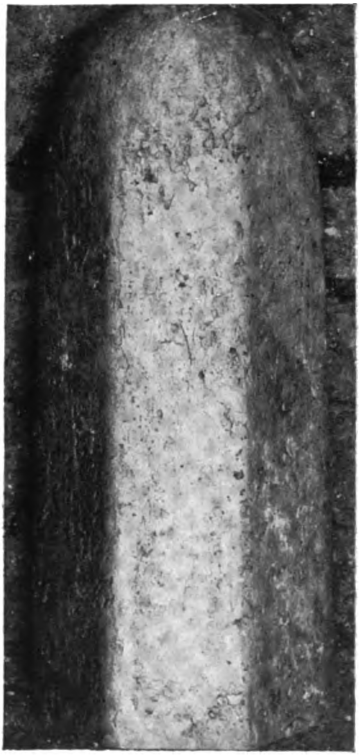

Fig. 2.—Surface of ingot B (page 282).

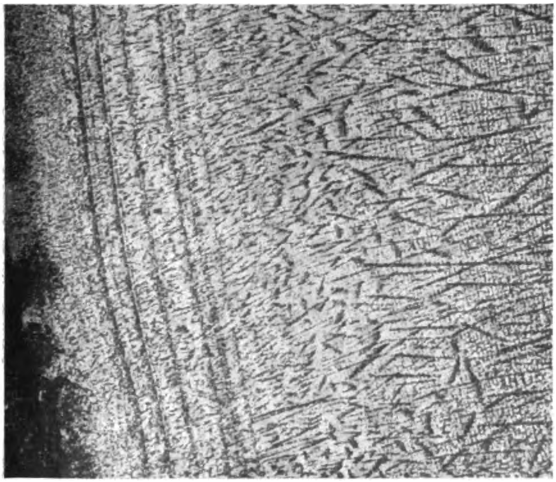

Fig. 3. × 4 diam.

N.B.—The reproduction of the etched surface by photography shows the reliefs light and the depressions dark, *i.e.*, as a negative of the prints.

Fig. 4.—Sulphur print of section shown in print 5 (reduced).

DISCUSSION.

Dr. A. **McWilliam** (Glasgow) congratulated the author on the results he had obtained. The subjects had constituted an important part of his (Dr. McWilliam's) work during the past year in India. One of his methods in connection with getting materials up to the quality required, was to suggest a mental picture in the minds of Indian teemers of what would be inside the ingot if they did this, that, or the other. He had used, not the beautiful kinds of printing exhibited in the paper, but his own rough sketches, and he had had to try, in Hindustani, to produce a picture of the internal structures of the various types of ingots in the minds of Indian workers, whose work was estimated to be worth 10d. a day. It had been extremely interesting to find that his old experience in making such things clear to backward students had been valuable to him in conveying them to the minds of the Indians who were eager to learn. He was able to produce by those means considerable improvement in the quality of the ingots made from a given type of molten steel, as shown by the reduction in the percentage of rejections of finished material.

He did not think perhaps that the wealth of detail shown in the paper would have been so good for his purpose as his own rough sketches, as it might have been confusing to the minds of the less highly trained Indian workers, but his own success with the rough method indicated the value that those detailed prints were likely to have for the highly trained.

People would say of ingots, "This will be welded up" and "that will disappear with sufficient forging or rolling," but it always seemed to him that in an ingot, as in a man's life, once something had occurred it never ceased to exert some influence on the final result, hence the great importance of the study of the ingot. He had ultimately trained the men to produce the required type wonderfully well, by the help of the examination of the nature of the top of the ingot as a guide in their work.

Dr. Stead recalled to his mind that Dr. Sorby of Sheffield was the first to make direct prints. Dr. Sorby showed examples of his prints some time in the sixties of last century, and he was sure he would have been delighted to see the way in which the process had been developed.

Dr. W. H. **Hatfield** (Sheffield) congratulated the author on his excellent paper. Right through the war those who had been working on the subject in Sheffield had been in touch with the author, and he had very kindly shown them from time to time the progress of his work. There was no doubt that macrostructure had now become as important as microstructure, and the author's advance in technique would materially assist in the production of first-class images, full size, of the larger specimens, which of course was a useful achievement. In many laboratories people were content with etching with different reagents and then photographing, but of course a photographic production would never be quite as satisfactory, being generally accompanied by light and shade, which somewhat diminished the value of the print. In his (Dr. Hatfield's) own laboratories he used 10 per cent. copper ammonium chloride in water, and found it a very effective etching medium, but the necessary deep etching effect was not readily obtained by their method. The author had spoken with apparent knowledge of the distribution of the phosphorus, suggesting etching effects produced by that element. He knew that Dr. Stead shared the author's opinion. He (Dr. Hatfield) did not feel convinced in his own mind that phosphorus was the element which was responsible for the macrostructure. Whether the phosphorus content was 0·01 or 0·05, the same effect was obtained. There were several other elements present in greater proportion than the phosphorus, and he thought it more reasonable to suppose that the effect of the sum total of the elements on the purity of the crystal during freezing would be the more likely explanation of the structure. The author did not deal in detail with the influence of chromium. It might interest him to know that he (Dr. Hatfield) had prepared a series of experimental steels not containing chromium and etched them in this way, and then prepared another and gradually added chromium. As soon as the chromium came in there was a very marked difference indeed in the structure, the acicular nature of the crystals at once appearing. The author referred to immobile carbides. He would like to know whether he used that expression as the result of deductions from actual experimental observation other than macrostructures. He himself always considered that chromium carbide, and in fact any carbide, would diffuse readily in iron at the temperatures to which steels such as those were exposed.

Mr. J. H. WHITELEY (Stockton-on-Tees) said the subject was one to which he had given a considerable amount of attention some years ago, and he had published some results in the *Proceedings of the Cleveland Institute of Engineers*.[1] The solution he used for etching large specimens contained 20 grammes of ferric chloride and 0·12 gramme of copper chloride in 100 cubic centimetres of water, and 10 cubic centimetres of hydrochloric acid. That reagent was really a modification of Dr. Rosenhain's. He had not tried the reagent described by the author, but he was inclined to think from the author's remarks that the particular reagent which he (Mr. Whiteley) had used was slightly better. The specimen was placed in a dish or etching tank, the reagent was poured on, and after about five minutes the specimen was taken out, dried, rubbed over with very fine emery paper, and then put back again. The etching could then be continued for half an hour or more and very deep impressions were obtained. The method he employed to obtain the prints was to rub Chinese white into the impressions, and set the specimen up in a good light and photograph it, but there could be no doubt the author's printing method was much better. With regard to the peculiar line which could be seen near the margins of some of the author's macrographs, that had also been pictured in the paper to which he (the speaker) had referred. That line represented a layer of purer material separating two types of structure—dendritic and granular. The conclusion he had come to at the time from various observations made on the structure of cast steel was that the granular structure was really due to a chilling of the metal as it entered the mould and not to any violent agitation of the steel, as stated by the author.

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[1] "A Study of Cast Steel," December 1914.

Fig. A in Plate XI. showed the macrostructure of a section of a cast steel cogging-mill guide which failed in use. The specimen was about 3½ inches wide and was etched by the reagent described above. Two structures were seen, one dendritic and the other granular; the latter showed no sign of any dendrites. The two structures were separated by a layer of purer material. Test-pieces 7 inches by 1 inch were cut from each side and gave the following results:

	Granular.	Dendritic.
Tensile strength (tons) . .	33·7	30·0
Elongation per cent. . .	25·0	6·0
Contraction per cent. . .	37·2	4·5

The bend-test (1 inch square section) of the granular material bent through 180° without breaking while that of the dendritic broke at 60°. It was certainly remarkable that such diverse results should be obtained from pieces taken so close together. Whatever may have been the cause of the granular structure, it seemed certain that it could not have been produced by a violent agitation of the metal in the mould. The analyses of the two parts were as follows:

	Granular. Per Cent.	Dendritic. Per Cent.
Combined carbon. . . .	0·245	0·24
Silicon	0·37	0·36
Phosphorus	0·054	0·055
Sulphur	0·041	0·038
Manganese	0·530	0·520
Aluminium	trace	trace

Dr. W. Rosenhain, F.R.S. (National Physical Laboratory), said the results the author had obtained were both beautiful and useful. With regard to the theoretical question as to the cause of the macrostructure, the position was such that a certain attitude of reserve had, he thought, to be maintained. No doubt any impurity which existed in a liquid solution of steel, and remained in the crystals in solid solution, would give rise to what the author called minor segregation. He was not sure that that was quite the happiest phrase for it, although the members would all know what it meant. The question was how long, in the future treatment of steel, pseudomorphs of that original dentritic structure of the crystals, the original coring of the crystals, would persist. It was not a question of how much of that impurity was present, whether 0·01 of phosphorus for instance, but of how much remained there after subsequent treatment. It was a question of the rate of diffusion. Le Chatelier's evidence, which he had brought forward recently, showed that oxide was one of the substances whose presence could give rise to that dentritic appearance in the steel as cast, and that the resulting difference of composition would persist after a considerable amount of heat and mechanical treatment. Dr. Stead's work had shown conclusively that phosphorus would do the same thing, and it was quite possible that there were other elements as well. From the point of view from which the author employed the process for studying the primary crystallisation and the flow of the metal, it was quite immaterial what the cause of that structure was. What was known was that there was a mapping out of the original crystallisation of the steel, and the lineal descendants of that original crystallisation persisted in the form of pseudomorphs of one sort or another, right through to the finished stage, and it was upon that fact that the value of the whole method depended. It was applicable not only to the ingot and to the forms having undergone comparatively small amounts of forging to which the author applied it, but it was applicable to such things as rails, tyres, axles, &c. By its means could be traced, in a most instructive way, the flow of the steel, the amount of work it had received, and the manner in which that work had been applied. It was possible, for instance, to say, when dealing with a cracked part, whether that crack had been formed before or after the last forging or hot rolling. If a crack had been formed before the last hot rolling the flow lines all stopped at the crack, whereas if it was formed afterwards the flow lines ignored the crack. It was most useful and important to be able to establish such facts at times. There were a number of other uses, and the method of direct printing undoubtedly had the very great advantage which the author claimed for it, of being palpably obvious even to what he described as the lay mind. He himself had had to deal with the lay mind quite often, and appreciated that point very much. There was one small matter he wished to mention with regard to the author's observation about the effect of the shape of the end of a punch in punching a shell blank—the fact that the resistance to a square-headed punch was actually lower than the resistance to a pointed punch. One would have imagined that the pointed punch would enter more easily, and would pass through the mass with a good deal less resistance, just as the pointed bow of a ship passed through water more easily than a blunt bow. Personally he had not been surprised to see what had happened in this case, because he had seen an example of a very similar action in another process, the process of extrusion.

In extrusion the metal was placed in a cylinder, and by means of a piston, pressure was applied. In that way it was forced to come out through a die as at D (Fig. B, below). The lines of flow could easily be shown. They ran in the sort of fashion indicated by the arrows shown, and one would have thought, judging by the analogy of hydraulics, that shaping the die so as to allow the metal to flow gradually and smoothly into it would have facilitated matters, and would have very materially diminished the resistance to flow. Experiments at once showed that the contrary was the case. If one made the die with a bell-mouth for instance, one not only very much increased the power which had to be applied to the piston, but as a result it led to such pressure on the die that the die itself cracked. The explanation was the same as in the case which the author had illustrated, and it was as follows—that unless the shape leading into the die was *exactly* conformable to the direction of flow, the shape did more harm than good, probably by increasing the area over which friction had to act. The best way to get the right shape was to let the metal form it for itself. What happened if a flat-faced die, or one with a slightly concave interior face was used? In the corner, near C in the fig., there was a region in which the metal underwent no flow at all. It simply sheared off along the direction of natural flow, and formed the right shape for easiest flow for itself, far more accurately than one could possibly form it by a die beforehand, because so much depended on the exact conditions of temperature and the stiffness of the metal. Possibly if success were met with in making the die just the right shape, advantage might be got from it, and no doubt the same applied to the punch in the author's case. In actual practice, the roughly guided shape which one made was worse than none at all. It was better to let the metal take its own course. It was rather an interesting analogy between the extrusion process, which he believed had not yet been

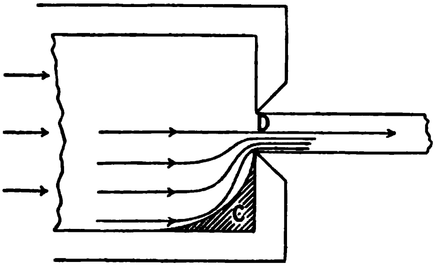

Fig. B.

practised in connection with steel, and the punching operation described by the author.

Dr. J. E. Stead, F.R.S., Vice-President, said the subject of the paper was most instructive and valuable to metallurgists. It might be well to trace briefly from the earliest times the actual history of the printing of macrostructures. Dr. Sorby was the first person to make macro prints from blocks that had been etched with acid, but the process was quite different from that described by the author. In the former case it was the cementite in the ingots which was left in relief, and gave the pattern on the printing block. Later on, a very excellent and valuable method of obtaining very much the same macrostructure, was obtained by an auto-sulphur printing process. It consisted of placing a piece of bromide paper impregnated with dilute sulphuric acid on the face of the surface of the polished steel. If sulphur prints had been taken of those very sections of which illustrations were given in the paper, the author would have got the same structure, but with the "tone" reversed. That was to say, what were whites in Mr. Humfrey's diagram would have been brown in the others. Mr. Whiteley had given him some blocks of steel deeply etched, which might well have been used for printing, because the insoluble parts were in such great relief. He did not think, however, they had been used as printing blocks. He would suggest that Mr. Whiteley should take one of his blocks and use it for printing, and send the print for publication in the Journal.[1] What was responsible for the difference in the solubility of different parts of polished steel? He (Dr. Stead) had been more or less made responsible for stating that it was invariably phosphorus. He had never made such a statement. He had pointed out that nickel and chromium and other elements led to differences in solubility. It was not necessary to have any chemical variation in the metal, for pure iron of large crystalline structure showed differences of solubility in different crystals. When a polished surface of pure iron containing fairly large crystals of iron was etched, certain crystals were to be found which were eaten into much more rapidly than others, and if one were to use the polished and etched plate as a printing block, one would get the same kind of variations shown by the author. The variation in solubility was due to difference in the physical orientation of the crystals themselves, the cube faces being less soluble than any other face. Macro-printing would be most valuable for all metallurgists and engineers, and for those who wished to see what was inside the steel.

Mr. E. H. Saniter (Rotherham) thought that those who had used the author's method should not let the present opportunity go by of expressing their sense of the great value of the process. His firm had used it mainly on forged materials. To use it on an ingot structure was perhaps somewhat superfluous. There the dentritic structure or the general macrostructure was so coarse that it was shown just as well by the ordinary sulphur print. About ten years ago he had exhibited the first sulphur print of a 25 cwt. ingot at a Conference in London. It showed all the characteristics of the chilled outer rim of the dentrites and the sagging of the centre during solidification. He thought that for smaller bodies and forgings the process brought out detail more clearly or abundantly than the ordinary sulphur printing process. If, for instance, drop stampers wished to produce the best article, it would pay them to make sections of their drop stampings and take prints of the description under discussion, to ascertain whether their dies were the right shape. He happened to have made, and he believed the author had made also, prints of some drop stampings which showed an absolutely dead area in one part of the stamping. There had been no flow of the metal at all, and it was quite unworked, and very coarse. One unfortunate feature about the method was that it was rather a long and expensive process to polish objects of any size for the production of the prints, and there was also the danger of producing false appearances during the etching, if the greatest care was not used. He himself in the works had seen appearances produced which absolutely appeared as if it must be in the steel, and had had the process repeated, whereupon they had absolutely disappeared. Those false appearances had a tendency to appear more particularly towards the edges of the specimen. It was just as well to sound a warning on a matter like that, because people might otherwise be misled.

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[1] This Mr. Whiteley has since done. See p. 289 *ante* and Fig. A, Plate XI.—Editor.

Mr. H. H. Ashdown (Newcastle-on-Tyne) said he felt under a debt of obligation to the author, as he had had that process in detail passed on to him, and had found it most useful in investigating sections of large ingots. He was much pleased to see that the author had not continued to describe his reproductions as phosphorus prints. Some little time ago he (Mr. Ashdown) had taken some of the sections which had been deeply etched, and had had them scraped and analyses taken in duplicate. He found that in several cases the sulphur had come out considerably higher in proportion than the phosphorus. There was one case in particular which might be of interest, where the sulphur from the back of the disc was 0·026, and that from the etched scrapings came out 0·06, while the phosphorus rose only from 0·02 to 0·031. He was sure there was a great future before the method, which was extremely useful in dealing with sections from very large ingots. Dr. Rosenhain had already explained the reason of the difference of the pressure required, in punching shell with a round-nosed punch as compared with a square-nosed punch. It had been his privilege some years ago to be in charge of shell manufacture, and he could assure the author that to use a round-nosed punch was a retrograde step. In using a round-nosed punch, owing to the excess pressure required, it was apt to bend, take a false lead, and much eccentric work would result. If after considerable use a round-nosed punch and a square-nosed punch were examined, one would see at once why much greater pressure was required. There was very heavy scoring all over the round-nosed punch, whereas with a square-nosed punch there was only evidence of friction flow past the shoulder, and in addition one got a direct push. With regard to the cones which had been found in the bases of shell, during his experience of shell manufacture he had had very many shells sectioned, and had never come across a cone, but had had one handed to him eighteen months previously, and from his examination he thought the author would find that they corresponded with the segregated cone in the ingot. He was disposed to think those cones, due to the applied pressure, slipped from the segregated area when the billets were punched on the cold side. During the war, owing to the great pressure in production, it was quite likely that many of those shell billets had been pierced at comparatively low temperatures, and what had actually happened was that the cone had been forced down from the segregated faces into the base. He did not think that, provided the billets were punched at a comparatively low temperature, the round-nosed punch would obviate the coning taking place.

CORRESPONDENCE.

Mr. J. H. S. **Dickenson** (Sheffield) wrote that he had used a method of macro-etching and macro-printing similar to that of Mr. Humfrey for several years, and had found the readiness with which a number of prints might be obtained from the etched section of an ingot or a forging very convenient and valuable. Dr. Sorby had actually obtained prints in a similar way from cross-sections of converted bar etched with nitric acid. Dr. Sorby's " nature prints," which were reproduced in the *Journal of the Iron and Steel Institute*, 1887, No. I., were not to be compared, for beauty, with those which could be obtained by the use of a cupric etching reagent, like the excellent examples with which Mr. Humfrey's paper was illustrated.

When, several years ago, Mr. Humfrey had kindly shown him (Mr. Dickenson) several small prints obtained by his process, he did not communicate the composition of the etching reagent used, and he (Mr. Dickenson) proceeded to experiment on his own lines, finally obtaining really excellent results from a distinctly different formula to that which, he now found, had been used by Mr. Humfrey. When, in Messrs. Vickers' Research Laboratory, it was desired to make a macroscopic examination of a steel surface, large or small, the usual procedure was first to take a sulphur print, next to etch with 10 per cent. solution of nitric acid in water, and then, without further preparation of the surface, to etch with a reagent containing:

Ferric chloride . . .	40 grammes.
Copper chloride . . .	3 ,,
Hydrochloric acid . .	40 cubic centimetres.
Water	500 ,,

That was continued until sufficient relief was obtained, when, by the use of printers' ink and paper, any desired number of prints might be taken. Preliminary etching with nitric acid had a double advantage, since the existence, or non-existence, of fine cracks, hair-cracks, or other similar defects, as well as structural variations due to heat treatment, were far better shown up by that reagent than any other, and, in addition, treatment with nitric acid made the subsequent cupric etching easier and more regular. Although laboratory assistants usually found considerable difficulty in getting satisfactory etchings when first using a cupric reagent, very dissimilar etching reagents gave, when properly handled, similarly excellent results. Skill in applying the reagent appeared, in fact, to be of more importance than variation in its composition. For most works purposes, the use of a printing press was out of the question, and it was usually necessary to ink with an ordinary hand-roller, pressing the paper on by a squeegee. That was not easy, but with practice perfectly evenly inked prints could be obtained from comparatively large ingot sections. No special difficulty had been experienced in the Research Laboratory of Messrs. Vickers, Limited, Sheffield, in obtaining satisfactory prints from ingot sections 18 inches wide and 60 inches long.

Mr. O. W. Ellis (London) wrote that the method described by the author was a welcome improvement upon that of Dr. Sorby, described under the head "Nature Prints" in the *Journal of the Iron and Steel Institute*, 1887, p. 259.

Dr. Sorby's mode of procedure was complicated by the implied necessity for cutting the specimens to type height. Other workers had since discovered that there was little need for such elaborate methods of preparation either in the cutting or the polishing of the specimens to be examined, and "nature prints," or, better still, macro-prints, had from time to time been produced with much less trouble than would be imagined to be the case from a perusal of Dr. Sorby's paper.

He (Mr. Ellis) had obtained many successful macro-prints by following a similar procedure to that described by the author in his paper. He had been fortunate in always having had at hand a printing shop to which he had been able to forward his etched specimens. He had hitherto employed Heyn's reagent, in the manner very clearly described in Bauer and Deiss' book on the Sampling and Analysis of Iron and Steel, except that he had allowed the chloride solution to remain in contact with the steel for periods varying from two to twenty-four hours. Generally speaking the longer periods had been found necessary to obtain perfection. It would be of interest if the author could confirm that the acid chloride bath was the quicker in action, as would seem to be the case from his statement on p. 279, lines 17 and 18. The author on p. 281 stated that only in those cases in which the microscope had given positive evidence of incipient fusion or burning had there been failure to obtain satisfactory prints by the method described. He (Mr. Ellis) wished to know whether in no other cases but in those referred to had difficulty in obtaining perfect etchings been experienced, as he had found that the application of even slight amounts of cold work created trouble in many instances.

It would be of interest to know the results of the author's further experiments on the analysis of scrapings from the relief portions of etched samples.

On p. 284 the author described the results of experiments on the flow of metal during forging, and stated that "in a completely sound billet the cone formation is probably unharmful." Did the author suggest that the formation of such a cone was an essential feature in forgings obtained when flat-nosed punches were employed in manufacture? That certainly did not agree with the writer's experience, which was that, provided material was homogeneous (in so far as material can be homogeneous) and uniform in temperature throughout its mass, flow would take place at all places, even in the immediate vicinity of the "flat" of the punch.

Mr. G. W. **Green** (Openshaw) congratulated Mr. Humfrey on his greatly improved method of macro-etching and printing. Macro-etching and printing had been known for some considerable time, and Howe described a method of etching by means of weak acid which he followed up by a printing process similar in principle to that of Mr. Humfrey. When Mr. Humfrey gave his (Mr. Green's) firm details of his method it was somewhat different from the present published account and involved at least three etches to develop the relief structure sufficiently for printing purposes. Some details of the technique as employed at Openshaw might be of interest.

The flat surface for printing was rapidly, cheaply, and easily prepared by first machining on a planer, finishing with a fine cut, and then buffing the machined surface. The buffing was done in the usual manner in the buffing-shop. Any inequalities of surface caused by buffing were very slight and gave rise to no difficulty whatever either in the etching or printing operations. A useful preliminary to the main etching process was a short etching with dilute nitric acid, which helped to get rid of any machine marks and gave a very good indication of what the macrostructure was like.

The use of a wash-bottle for applying the etching reagent tended to greater cleanliness and economy. Should the copper film tend to stick, rubbing with a piece of cork would clear it away easily.

PLATE XI.

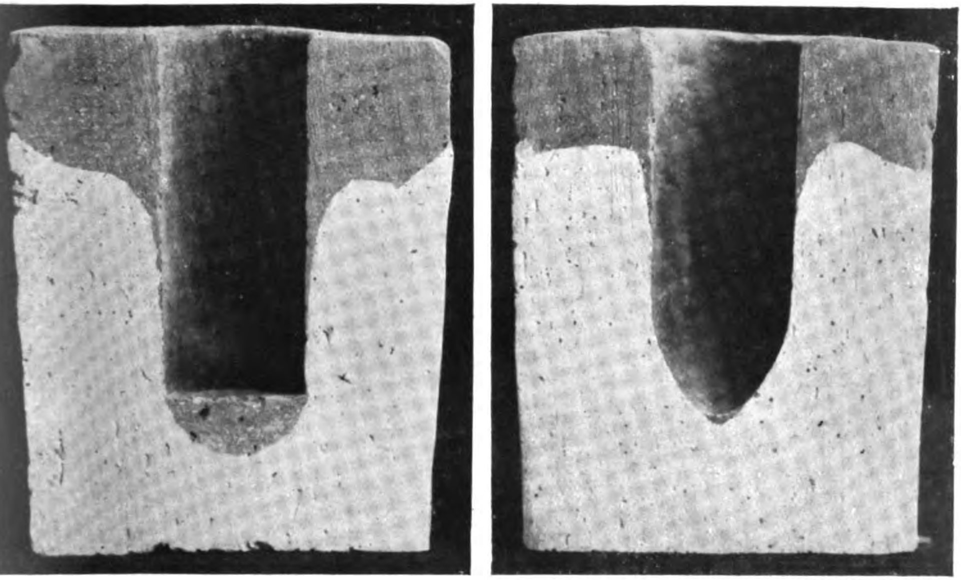


Fig. A illustrating Mr. Sumner's remarks.

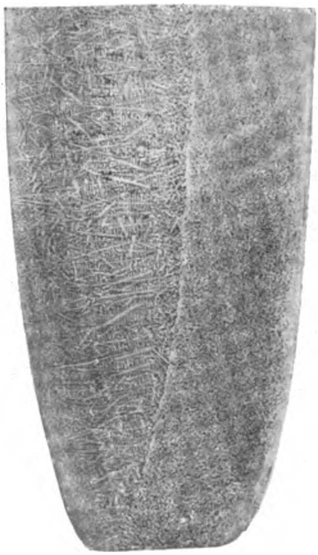
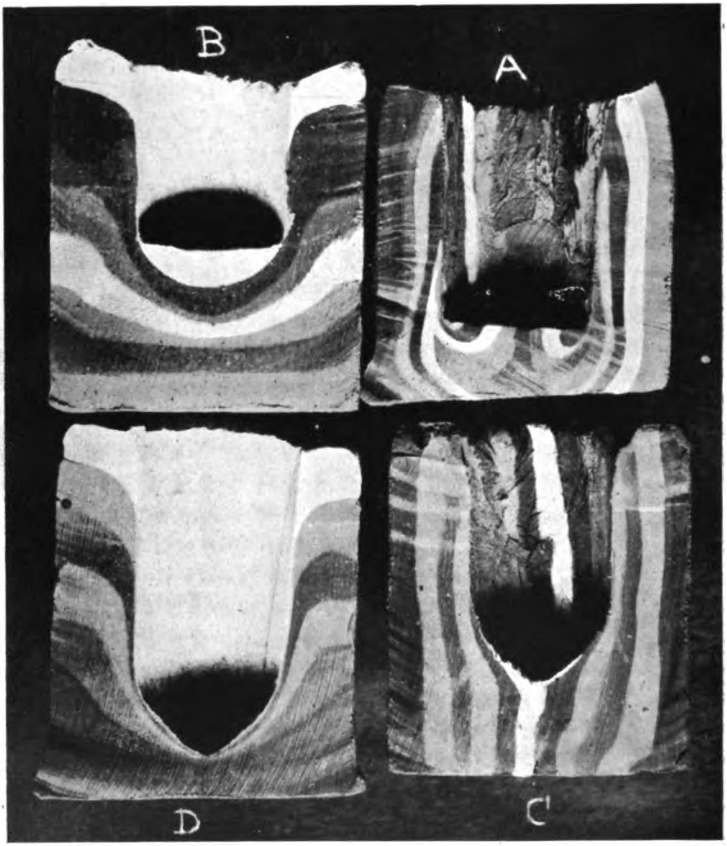


Fig. B.—Macrograph illustrating Mr. Whiteley's remarks.

To face p. 296.



Plasticene models illustrating Mr. Humfrey's reply to the discussion and correspondence on his paper.

The great difficulty in the printing was to estimate the correct quantity of ink for obtaining a good print. The best way, especially where a number of prints were required, was to have just a little too much ink on the roller and specimen for the first print, which should be rejected, and then, without re-inking the roller, go over the specimen again. A print after that operation was usually a good one, and by judicious use of the roller three or four more good prints could be obtained without re-inking. For clear reliefs and quick clean working the specimen was in its best condition in the "as cast" state, or, if it had been mechanically treated, in the "as forged" state. It was in its worst condition in the hardened or hardened and tempered state.

Some wonderful pioneer work in interpreting macrostructure had been done by Belaiew and Howe. Belaiew's conclusions that the effect of any ordinary heat treatment was negative was fully confirmed by Mr. Humfrey's statement to the effect that even up to incipient fusion the dendritic structure or the results thereof were unalterable.

The analyses showing the small difference in phosphorus content between the normal metal and the scrapings from the relief were very interesting. Apparently Mr. Humfrey expected a greater difference, but such was not necessary because, with the admitted delicacy of his cupric reagent, a small difference in phosphorus caused a big etching difference. In investigating, by Mr. Humfrey's method, a steel containing a number of fine ghosts, he (Mr. Green) took the opportunity of making analyses both from the normal metal and from the actual ghosts. Although ghosts were supposed to contain a high percentage of phosphorus the two analyses showed 0·046 and 0·067 phosphorus respectively.

A proof of the delicacy of Mr. Humfrey's reagent could be deduced from the fact that it etched to perfection the chill crystal area of an ingot. The chill crystals and the filling of the interstices had of necessity solidified very quickly. Consequently the phenomenon of differential solidification had been stopped to a great extent, and so the metal was much more homogeneous than would be the case with a normal solidification. In spite of the resulting small difference in composition the relief was sharply defined and gave good prints. From the fact that chilling did not appreciably stop dendritic growth it would seem that such a growth would be difficult to suppress. Belaiew had proved that steel water-quenched from the liquid state still exhibited, upon etching, perfectly formed and well-defined dendrites. That again went to show that considerable etching differences did not mean very appreciable differences in composition. It would be interesting, although very difficult, to obtain information as to the rate of growth of dendrites in steel under varying conditions. A study of the rate of growth of ammonium chloride crystals was instructive and showed the extreme rapidity with which they could grow.

He (Mr. Green) was not quite satisfied with Mr. Humfrey's explanation of the lines which ran parallel to the surface of ingots B (Prints 2 and 4). Mr. Humfrey said that they were due to successive skins being formed above the general level of the liquid, yet where those lines were most marked was right at the bottom of the ingot (Print 2). It seemed fairly obvious that a skin could not form in that position above the general level of the liquid, and owing to the mould being of such a small cross section at that point the metal could not form a skin before any more metal flowed above it. Neither did Mr. Humfrey's explanation account for more than one such line and yet in places there were several, nor did it seem tenable with the fact that the lines were so uniformly parallel—both with one another and with the ingot surface.

Referring to Print 6, Mr. Humfrey suggested that a conical piece of steel from the top of the billet was pushed right down in front of the punch "practically without deformation." "Apparently without deformation" would have been more correct. The writer had come across several instances where the prevalent direction of the lines of the macrostructure had been parallel to the direction in which the punching or forging had been applied. In all these cases the distortion had been apparently very small. On close examination, however, it was found that such dendrites as were more or less parallel to the direction of work were stunted, whilst others were greatly elongated and tended to twist round into a position at right angles to the direction of the application of work. It was obvious that the dendritic structure of a steel would, on mechanical treatment, tend to be distorted, so that the prevalent direction of the resulting structure would be normal to the direction of the application of work. Such dendrites or lines as were parallel to that direction would either be bent through an angle of about 90° or would first become very squat and then elongate in a direction at right angles to their original position.

Did Mr. Humfrey think it possible to get a steel free from dendritic or rather casting structure? It was possible to conceive that an absolutely pure iron-carbon alloy might be so. Even then the casting structure would form, but owing to diffusion of the carbon during cooling there would be no pseudomorph after the casting structure.

It was possible that the structure resulting from the distortion of the dendrites was beneficial in such sections as, for example, girders. Because of the work put upon the metal the heterogeneity was similar to that of wrought iron, the slag fibres being replaced by the greatly distorted dendrites. A better longitudinal test was therefore obtained at the possible expense of the cross test, the difference being due, of course, to the form taken by the macrostructure. The structure was harmful when very sharply defined and when the minor segregation was great. Whether beneficial or otherwise, he (Mr. Green) considered that dendrites were at their best when they were as fine and small as possible. That, of course, raised the difficult question of scientific casting control.

Mr. N. P. P. **Sandberg** (London) wrote that it gave him great pleasure to see that Mr. Humfrey's most valuable process was now being made public through the Institute. It had proved of the greatest assistance during the war when, as Director of Inspection of Steel in the Ministry of Munitions, he was frequently called on to investigate defects and faults in shell steel, and shell and gun forgings. The extreme delicacy of detail in Mr. Humfrey's method frequently gave his department the necessary clues to the solution of problems which other processes had failed to solve. Referring, for example, to Print 6 and Fig. 5, longitudinal sections of shell forgings might, after surface polishing, appear perfectly sound and homogeneous to the eye, but would show the presence of a "cone" upon a sulphur print. Only, however, after etching by Mr. Humfrey's method was the structure of the cone revealed, showing its entirely different formation from that of the surrounding mass, and confirming its creation and presence as an automatic temporary nose-tip to the punch conforming to the flow-lines of the surrounding metal.

The process should prove of inestimable value to steel-makers and engineers generally, and particularly as suggested by Mr. Saniter, in showing whether the metal in forgings was being made to flow to the best advantage.

Mr. E. H. **Sumner** (London) wrote that with reference to Mr. Humfrey's most interesting paper some points in connection with "Case III." called attention to a serious defect resulting from the use of flat-faced punches in the forging of shell blanks. It had frequently been observed that a flat-nosed shot would penetrate freely into a bank of clay, and that was accounted for by assuming that on striking the clay the shot formed for itself a clay nose which enabled it to drive into the mass with a minimum of friction.

In forming shell blanks with a pointed or round-nosed punch the heated metal of the bloom was steadily displaced by the punch throughout its passage, but the action of a flat-faced punch was similar to that of the shot above referred to. On coming in contact with the bloom the punch appropriated the necessary metal to form a suitable nose with which it then proceeded to displace the metal in its path until the end of its stroke, and, on being withdrawn, left the extemporised nose at the bottom of the cavity. Moreover, it would appear that the slip of the metal around that false nose destroyed cohesion, and consequently the nose-piece might be likened to a separate piece of metal which at best might become welded to the mass, but was frequently only partially welded thereto or even quite loose.

The accompanying photographs illustrated clearly the effect of the punches. They were obtained from plaster of Paris cylinders having the upper portion coloured by the admixture of red-lead, punched while in a plastic condition, allowed to set hard, and then sectioned (Fig. C, Plate XI.).

Mr. J. C. W. HUMFREY, in reply, wrote that he greatly appreciated the discussion and correspondence to which his paper had given rise, especially in the case of contributors who stated that the methods described had been of value to them in investigating practical problems in works. He had not been aware that direct contact printing from etched surfaces had been previously described and practised by Dr. Sorby. Probably if he (Mr. Humfrey) had known that it would have helped him considerably in his early experiments.

. In replying to the various points raised, it would perhaps be more convenient to deal with them under subject headings, than to discuss the remarks of each contributor in turn.

The Etching Solution.—The acid cupric reagent described was adopted after numerous trials with various formulæ, including some containing ferric chloride, similar to those described by Messrs. Whiteley and Dickenson. While the etching was possibly quicker with such modifications of Rosenhain's reagent, the difficulty of removing the copper was found to be greater, and generally they were not under such complete control. He was inclined to think, also, that they were not quite so sensitive in revealing the finer details of the structure,

Neutral copper ammonium chloride solution (Heyn's reagent), at least when used for plain carbon steels, was not considered a very satisfactory reagent, especially for the production of prints; its selective action was slight, and the relief effects were (as stated by Mr. Ellis) only obtained with very prolonged attacks, thus leading to waste of time and solution. With alloy steels containing chromium, Heyn's reagent would produce relief effects fairly quickly, but offered very little advantage over nitric acid, and was decidedly more expensive.

Technique.—There was no doubt that, in order to obtain successful etchings and prints, a good deal of patience was necessary until the small details of the process were understood. The original preparation and finish of the surface were frequently a source of difficulty; and—as mentioned by Mr. Saniter—in the case of large specimens somewhat expensive. The false results Mr. Saniter referred to were usually found to arise from dry grinding or similar forms of surface distortion, or from the use of a solution containing too much acid. In the former case a preliminary etching with nitric acid or the neutral reagent always gave a clear indication of the defects, and the acid cupric reagent should not be employed until they had been etched away. The general routine procedure for macro examination (of sulphur printing, etching with nitric acid, and finally with an acid reagent), such as described by Messrs. Green and Dickenson, was certainly the most useful, and had, indeed, been constantly followed in his (Mr. Humfrey's) laboratory.

The Origin of Macro-Structure.—As stated in the paper, the author agreed with many of the contributors that it was unwise at the present time to lay down definitely what were the elements whose unequal distribution was responsible for the effects produced by acid cupric reagents

His views on that subject were similar to those so clearly expressed by Dr. Rosenhain. Two properties would appear, as Dr. Rosenhain stated, to be essential, viz. (1) that of existing in solid solution, and (2) that of only diffusing at a very slow rate. The first consideration would appear to rule out sulphur. While that impurity was known to be distributed in practically the same manner as those which did influence the action of acid cupric reagents (*vide* Print 5 and Fig. 4), and indeed might be in relatively higher proportions in the segregated areas than say phosphorus, the fact that it was present in isolated particles, and not in solid solution, must prevent it taking part in the wonderfully graduated action which occurred. The second consideration ruled out carbon, except in the case of alloy steels in which special carbides were formed having relatively slow rates of diffusion. In such steels the neutral reagent, or even nitric acid, would produce marked relief etching.

In reply to Dr. Hatfield, that unequal distribution of carbides in dendritic form could frequently be seen in micro-sections etched with picric acid, and was also revealed by the effects of strain; bender test pieces from nickel chrome forgings were, for example, frequently marked all over the strained surfaces with a distinct dendritic pattern in low relief.

Dr. Stead was mistaken in saying that macrographs made by the method described were the reverse of sulphur prints as regards light and dark areas. In both cases the segregated areas appeared dark (*vide* Print 5 and Fig. 4).

Examples, *Case* I.—Messrs. Whiteley and Green were not prepared to accept the author's explanation of the skin seen round ingot B, but did not offer any alternative explanation beyond chilling. If such an effect were to be ascribed entirely to the chilling influence of the mould, it would be difficult to understand why its presence should not be universal, instead of being confined to the case of certain ingots in which other results of rapid pouring, such as bad surface, were also present. The chilling effect of the mould upon a steadily rising column of liquid steel must necessarily be continuous, and would only result—as it had done in the case of ingot A, in dendrites starting immediately at the surface and growing uniformly inwards. The skin in ingot B indicated a definite discontinuity in the solidification, marked by the line of purer metal separating it from the well-developed dendrites within. The whole appearance suggested that the surface of the skin presented a definite and sudden chill to the main mass of metal, and therefore to the view that that surface had been cooled by exposure to the air or other causes before the main mass of metal came in contact with it. One was therefore led to the idea that the skin represented metal splashed or surged above the mean rising level, which had solidified before it became submerged. Molten metal originally striking the base of the mould would be thrown out sideways and would produce a similar if not more decided skin over the bottom;

while both on the sides and bottom the surging might result in a series of such skins being formed before submergence was complete. Thus the fact that a series of lines were present in certain places (chiefly round the bottom) did not negative the explanation advanced.

He (Mr. Humfrey) was unable to follow Mr. Whiteley's distinction between a "granular" and a dendritic casting structure. The dendrites—according to the direction and spacing of the isothermal lines—might be either equiaxial or elongated, but he had never examined any cast steel—even small 1" trial ingots, cast in a heavy chill—in which the tree-like inner formation of both types was not clearly revealed by suitable etching.

It was suggested that the case of the cast steel cogging mill guide described by Mr. Whiteley might have been caused by double pouring, the portion described as "granular" being poured first, and allowed to solidify and grow practically cold before the remainder was introduced, to which it would then act as a chill.

Case III.—Several contributors to the discussion had expressed doubts as to the theory that the cone formation in the base of a punched shell blank was due entirely to the action of a flat-nosed punch. He would suggest that a little time spent upon a few simple model experiments with plasticine or some similar substance would soon dispel those doubts. The results of a few such experiments were illustrated in the accompanying photograph (Plate XIA) and might be used to discuss several interesting points arising out of the process. The blanks "A" and "B" were forged with a flat-nosed punch and the blanks "C" and "D" with a conical-nosed punch. In the case of "A" and "C" the "billet" was made of layers of different coloured plasticine arranged parallel to the axis, in the case of "B" and "D" the layers were originally at right angles to the axis. The correspondence between the distortion of the originally vertical layers in "A" and the author's original (Fig. 5B) was complete; while it would be seen that in "C" the distortion had proceeded in an entirely different fashion, and the result was clearly comparable with Print 7. "B" and "D" brought out several points which could not be so easily deduced from the previous illustrations. The most important, and one upon which it appeared to him (Mr. Humfrey) that several contributors had gone astray, was the fact that neither with the flat nor the conical-nosed punch was there any sign of discontinuous shear having occurred between any two surfaces within the "steel" itself, such as would necessarily take place between the surfaces of steel and punch. In both cases, for example, the top layer had remained unbroken—though in places very attenuated—and the interiors of the punched cavities were entirely and completely lined with the white plasticine used for the top layer. The difference in action between the two forms of punch chiefly affected the position at which the maximum axial compression occurs in relation to the base of the cavity. With the conical form the maximum compression occurs practically coincident with the face of the punch, but with the flat form it occurs some distance below it. The position of maximum axial compression with a flat-nosed punch was noted in the original paper, and as there stated was the peculiar deformation of the axial action which was the cause of loose cones resulting from unsound billets. In the case of a sound billet the cone formation would necessarily occur in a precisely similar fashion, but the formation was purely a matter of the direction of the minor segregates and, apart from a possible tendency for the steel to fracture more easily along their length, could not be considered as particularly harmful.

Mr. Sumner, in spite of his experiments with plaster, would appear to hold the view that a definite mass of metal adhered to the front of a flat-nosed punch, and was then bodily sheared through the remainder of the billet. He (Mr. Humfrey) was convinced that no such action occurred, and therefore that Mr. Sumner's fears as to the welding up of the cone to the base did not arise, since, provided the billet were sound, the two were never parted. He (Mr. Humfrey) was inclined to extend that view to the case of extrusion described by Dr. Rosenhain. In that case the action of the square-fronted die was not that the metal adjoining it formed a definite stationary natural shape through which the remainder flowed as through a nozzle, but that it acted by eliminating all such discontinuous shear, whether between either die and metal or between two surfaces of metal, and replaced it by uniform flow in the metal itself. The whole of the metal in the billet underwent deformation, and it would be found that if an extrusion experiment were performed with a plasticine billet made up like those in "B" and "D" then right up to the end of the stroke the extruded metal would be sheathed in a complete external layer of the material which was originally adjacent to the die.

In the case of both shell punching and extrusion, the conical form resulted in motion and friction between surfaces of hot metal and cold punch or die, while the square form practically eliminated such motion and transferred it to the microscopical slip surfaces (or other mode of deformation) in the interior of the metal itself. One necessary distinction should however be drawn between the two cases:—In extrusion the mechanical advantages of the square-faced die probably outweighed the particular disadvantages—if any such occurred—resulting from the nature of the deformation applied to the billet, and its influence upon the macro structure of the extruded bar. In shell punching, however, one was faced with the unavoidable consequence that a flat-nosed punch would result in a loose cone in all unsound billets, and since with the best of intentions such unsound billets could not invariably be discovered before forging, it would appear preferable to accept the mechanical disadvantages of the conical punch as the lesser evil.

THE MANUFACTURE AND WORKING OF HIGH-SPEED STEEL.

BY J. H. ANDREW, D.Sc. (CHIEF OF THE METALLURGICAL RESEARCH DEPARTMENT, SIR W. G. ARMSTRONG, WHITWORTH & CO. LTD., OPENSHAW),

AND

G. W. GREEN (ASSISTANT IN THE METALLURGICAL RESEARCH DEPARTMENT, SIR W. G. ARMSTRONG, WHITWORTH & CO. LTD., OPENSHAW).

UPON the theoretical side of high-speed steels information is not lacking. Osmond, Bohler, Arnold, Carpenter, Edwards, Swinden, Honda, Yatsevitch, and others have dwelt at some length upon the question of tungsten and chrome tungsten steels from a scientific standpoint. The only papers, as far as the authors are aware, dealing with the subject from a practical point of view are those of Taylor-White and J. M. Gledhill.

It was thought that it might be of some interest to present an account of more recent practice of high-speed steel manufacture.

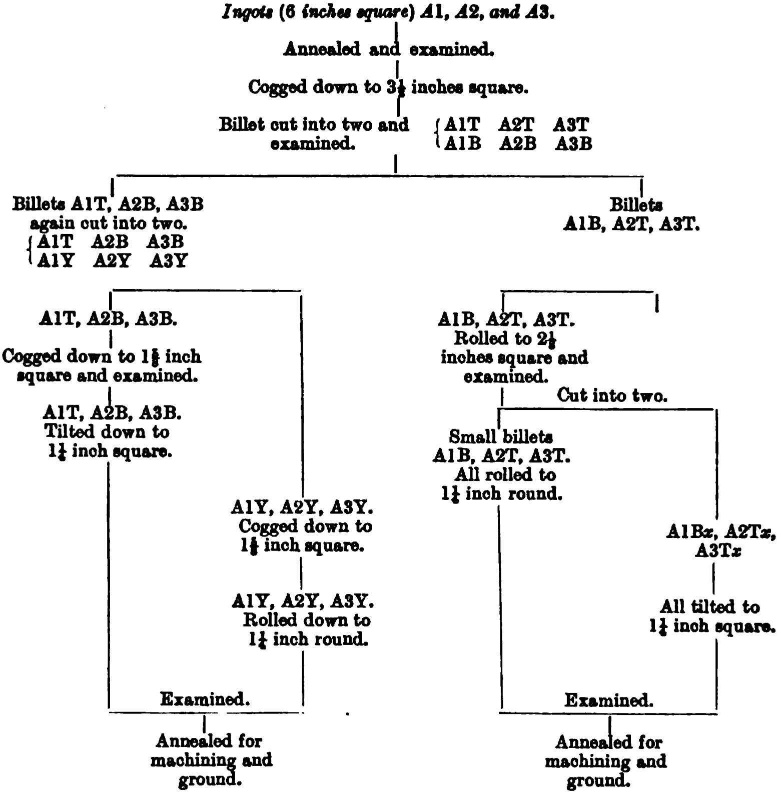
In this paper an attempt is made to show the practical applicability of scientific methods to high-speed steel practice, following through the steel from the state of ingot to the finished tool, and to show the changes that are brought about by the varying treatments.

The paper itself deals with four particular ingots of A.W. steel which were followed through every process, observations being made of times and temperatures of carrying out each particular operation, along with a micro examination of the steel after each successive treatment. The ingots chosen for this purpose were 6-inch square chills about 3 feet in length.

It must be stated that the figures given represent the practice as carried out at the Openshaw Works of Sir W. G. Armstrong, Whitworth & Co. Ltd.

In order to present all the phases occurring in the practical working of the steel it was decided to treat all four ingots in different fashions.

A table representing the operations undergone by the ingots that were followed is given below and on p. 307:

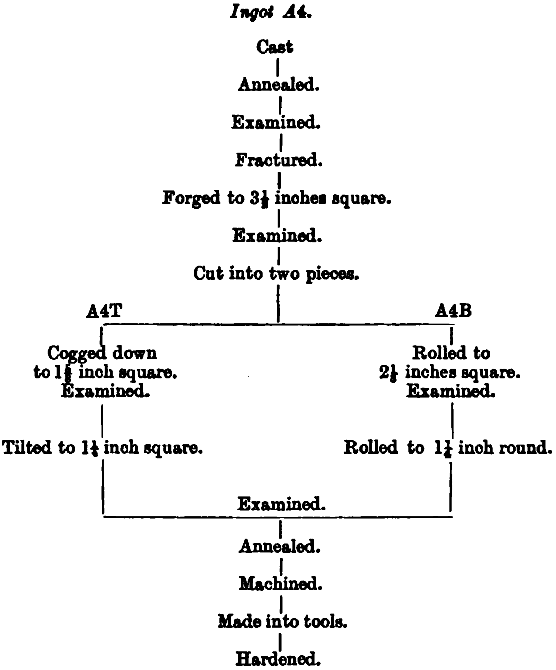

Ingots (6 inches square) A1, A2, and A3.
Annealed and examined.
Cogged down to 3½ inches square.
Billet cut into two and examined.
A1T A2T A3T
A1B A2B A3B
Billets A1T, A2B, A3B again cut into two.
A1T A2B A3B
A1Y A2Y A3Y
Billets A1B, A2T, A3T.
A1T, A2B, A3B.
Cogged down to 1⅝ inch square and examined.
A1T, A2B, A3B. Tilted down to 1¼ inch square.
A1Y, A2Y, A3Y. Cogged down to 1⅝ inch square.
A1Y, A2Y, A3Y. Rolled down to 1¼ inch round.
Examined.
Annealed for machining and ground.
A1B, A2T, A3T. Rolled to 2½ inches square and examined.
Cut into two.
Small billets A1B, A2T, A3T. All rolled to 1¼ inch round.
A1Bx, A2Tx, A3Tx
All tilted to 1¼ inch square.
Examined.
Annealed for machining and ground.

All tools made from the above hardened and put into service.

In order to make it easier to follow the various data obtained during the operations of mechanical and heat treatment of these ingots, the results have been tabulated under different heads. The separate tables will only be dealt with briefly as they are self-explanatory.

The pyrometer used was the Cambridge optical, standardised by the National Physical Laboratory. This pyrometer was found in practice to yield exceedingly reliable and concordant results, the results being slightly on the low side owing to the impossibility of obtaining perfect black body conditions.

A comparison made between the pyrometer in question and a calibrated thermocouple working in connection with a Paul indicator, gave the following results, and shows that a correction of *plus* 20° C. is required when employed for furnace temperatures.



Temperatures taken in Water-cooled Port of Basic Open-hearth Furnace.			Temperatures taken in Tool Steel Hardening Furnace.		
Optical.	Thermocouple.	Correction for Optical.	Optical.	Thermocouple.	Correction for Optical.
Degrees C.	Degrees C.	Degrees C.	Degrees C.	Degrees C.	Degrees C.
1100	1120	+ 20	1130	1150	+ 20
1140	1160	+ 20	1130	1155	+ 25
1215	1230	+ 15	1140	1160	+ 20
1240	1255	+ 15	1110	1140	+ 30
1300	1320	+ 20			
1340	1355	+ 20			

The above temperature comparisons are representative of a large number.

In the case of forging temperatures, according to Burgess, a slight correction of about 20° C. must be made. All temperatures recorded, however, are those actually observed.

In coal-fired furnaces, owing to the smoky conditions prevailing, no attempts were made at temperature determinations.

CASTING DATA.

After dead melting the metal from several pots was transferred into a ladle, from which it was teemed directly into the mould (top cast).

The temperatures of casting are naturally subject to various corrections, the temperatures taken in the pots being approximately correct. The temperatures of the metal in the ladle, on account of the surface not approaching black body conditions, are decidedly low, whilst the usual troubles from fume and emissivity errors are not accounted for.

The temperatures are, however, comparative.

The data—Table I.—serve to show the great uniformity obtained in casting temperature. Moreover, the annealing given to the ingots immediately after stripping showed remarkable uniformity.

The annealing was carried out in a gas-fired furnace.

Ingot A4 was the only one from which a piece could be got sufficient for examination. The type of fracture, microstructure, and macrostructure are given in the last column of the table, whilst the photomicrographs 1 to 3 are taken from different parts of the annealed ingot, and afford some interesting data which will be considered separately.

MICROSTRUCTURE OF CAST INGOTS AFTER BEING ANNEALED. (Plate XII.)

Micro 1 is the structure near to the edge of the ingot. Micro 2 is taken at 1 inch from the surface.

The white parts of these micros consist of the exceedingly hard double carbide of tungsten and iron (or, maybe, treble carbide of iron, chromium, and tungsten). It is seen that, near

TABLE I.—*Casting Data.*

No.	Size of Ingot.	Weight.	Time of Casting.	Temperatures.		Stripped.		Type of Ingot.	Annealed.		Fracture, Microstructure, and Macrostructure.
				In Pots.[1]	Ladle.	Time.	Temp.		Time.	Max. Temp.	
		Cwt.		Degrees C.	Degrees C.	Min.	Degrees C.		Hours.	Degrees C.	
A1	6″ sq.	3½	20 sec. 0·55 ton per min.	1410 1420 1430	1340	30	650	Good	48	800	The following particulars relate only to A4 and after annealing.
A2	6″ sq.	3½	17 sec. 0·62 ton per min.	1410 1420 1420	1330	30	650	,,	48	800	*Fracture.*—Trans-crystalline. Crystal grains are large. No chill crystals, but signs of chilling right to the centre.
A3	6″ sq.	3½	17 sec. 0·62 ton per min.	1410 1440 1440	1330	30	650	,,	48	800	*Macrostructure.*—No dendrites whatever. No sign of chilling. The carbide boundaries are in relief.
A4	6″ sq.	3½	18 sec. 0·58 ton per min.	1400 1430 1420	1330	30	650	,,	48	800	*Microstructure.*—Etched nitric. Near the ingot surface is a marked segregation of massive carbide. Shows eutectic structure. General structure, polygonal grains which increase in size towards the centre. The grain boundaries are of carbide. They become thicker and more discontinuous towards the centre and often show the eutectic structure. The ground-mass is a dark etching constituent and contains specks of free carbide.

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[1] These temperatures were taken in different pots as the lid was taken off and before the metal was poured. The conditions approximated more nearly to black body than when the metal was in the ladle, consequently the value is higher. Save for the correction for emissivity, these figures are nearly correct.

to the edge, these carbide envelopes are moderately fine and surround the small crystal grains. Towards the centre the grains increase in size, whereas the carbide envelopes become more massive; right in the centre of the ingot they are of considerable size. At certain places in the centre of the ingot segregation of this carbide is apparent, as is shown in Micro 3.

Micro No. 4 was taken at the extreme edge of the ingot. It shows on this section an excessive carbide segregation. It is seen that this segregate ends very abruptly, and its place is taken by an exceedingly fine and homogeneously distributed structure. No. 5 is taken a little way from the edge and shows the dendritic structure exceedingly well.

The conclusions to be drawn from these micros are: firstly, that on the extreme edge excessive carbide segregations occur. Nearer in than this, a fine structure persists, whilst in the centre of the ingot the usual coarse-grained structure with the thick walls of carbide is prevalent. It will be interesting to follow up this structure and to observe how it is broken up by mechanical work.

Cogging Down of Ingot to 3½-inch Square Billet.

The ingot after casting and annealing was cogged down to 3½ inches square under a 30-cwt. hammer and about 10 per cent. of the head cropped off. The results of the observations taken in this operation are given in Table II. Previous to the actual working of the metal the ingots were, before finally heating up for the forging operation, preheated in a gas furnace, being allowed about twenty-four hours to attain a temperature of about 820° C.; they were then immediately transferred, without cooling, to a coal-fired reheating furnace, where, after a period of four to five hours, they attained a temperature of about 1170° C. The time taken in forging varied between very small limits, and on an average was about 4½ minutes. The final temperature after all work was done was approximately 1000° C. After this, as after every other operation, the billet was examined and any cracks apparent were gouged out by means of steel gouges. The type of fracture and microstructure are shown in the last two columns.

TABLE II.—*Cogging down of Ingot to 3½-inch Square Billet.*

No.	Preheating.		Reheating.		Forging Operation.				Type of Billet.	Fracture.	Microstructure.
	Time.	Max. Temp.	Time.	Max. Temp.	Time.	Max. Temp.	Temp. most Work done.	Final Temp.			
	Hrs.	°C.	Hrs.	°C.	Min.	°C.	°C.	°C.			
A1	24	820	4½	1180	B. 6½ T. 3½	1150 1135	1070 1080	950 1050	2 gouges. Good. No gouges. Good. Very little grinding.	At the outside the grain size is small but it gradually enlarges towards the centre, where it is very coarse and typical of the overheated tool steel. Fracture is crystalline.	Ground-mass austenite almost decomposed. Acicular structure. The carbide envelopes of the cast structure have been elongated, as also have the carbide segregations. Near the surface the envelopes have been almost completely broken up.
A2	4	820	5	1170	B. 4 T. 3½	1145 1145	1060 1090	1005 1030	Good. 1 gouge. Good. Very little grinding	B. At the outside the grain size is very small and gradually enlarges towards the centre, but at the centre is a very definite circular patch (1 inch diam.) which is much finer than the rest. T. Round the outside of the fracture the grain size is very small and enlarges towards the centre.	Ground-mass of decomposing austenite. The grains are small but well defined. The carbide envelopes of the cast structure are elongated. Near the surface the grain envelopes are, to a large extent, obliterated.
A3	24	820	4½	1180	B. 4½ T. 4	1150 1155	1070 1075	1020 1000	Good. Good.	B. Fracture fine throughout. Crystalline. T. Round the sides the fracture is fine and grain size small, but towards the centre it enlarges.	Austenite decomposing. The austenite grains are small and well defined, and the acicular structure of the decomposition product is sparse and fine. The carbide envelopes are elongated. Near the surface the grain envelopes are broken up to a great extent.
A4	18	750	1 hr. 23 min.	1160	B. 5 T. 4½	1100 1110	1020 1080	980 1040	Good. 4 gouges. Fair.	B. and T. Fine crystalline at both ends with no enlargement of grain size to the centre.	Austenite decomposing irregularly; hardly taken place near the grain boundaries, which are elongated. Grain boundaries broken up near the surface.

MICROSTRUCTURE OF 3½-INCH SQUARE BILLETS.

Micro 6 shows the structure near to the surface, where the carbide envelopes are seen to be well broken up. Nearer to the centre of the ingot, however, where the carbide envelopes, due to the slower cooling, are thicker, they assume, after this treatment, varying shapes, and are most uniformly distributed.

Micro 7 indicates the appearance assumed by these carbide segregations and No. 8 appearance of carbide envelopes, embedded as they mostly are in a ground-mass of semi-decomposed material.

Occasionally one comes across a patch entirely free from these carbides and almost austenitic in structure. It was noted that in nearly every case near to the carbide segregation there existed these patches of undecomposed material (see Micro 8).

COGGING DOWN FROM 3½ INCHES TO 1⅝ INCHES.
(Table III.)

After cutting into two the 3½-inch square billets, they were aired under the fire-bars and finally charged into a coal-fired furnace. No definite time can be given for soaking, the times varying according to the ability of the forge to cope with them; nor was it possible in any of the operations carried out in the coal-fired furnace to get any reasonable temperature measurements. Here again, as in all previous cases, a glance at Table III. will show the great uniformity of the temperatures employed and the times in forging.

After forging one end the other end was charged into the furnace, followed, of course, by a similar forging.

All the forgings followed through were exceedingly good. Forging was carried out under a 1-ton hammer.

It must be remarked in passing that the term "over-heating" in the fracture column is used to describe a typical kind of fracture common to overheated steel; it does not mean that the bars in question were overheated, but is merely used to describe large grain size.

Two microstructures are shown of bars after this operation, namely, Nos. 9 and 10. From Micro 9 it is seen that the carbide

TABLE III.—*Cogging from 3½ Inches Square to 1⅝ Inches Square.*

No.	Forging 1st End.			Forging 2nd End.			Type of Forging.	Fracture.	Microstructure.	Brinell.
	Time.	First Temp.	Last Temp.	Time.	First Temp.	Last Temp.				
	Min.	Degrees C.	Degrees C.	Min.	Degrees C.	Degrees C.				
A1T	2	1150	1090	1½	1130	1100	Very good. No grinding required.	Similar to hardened tool steel fracture.	Austenite decomposing. The carbide envelopes are elongated into lines. A few segregations. Free carbide distributed irregularly	
A1Y	2	1140	1090	1½	1150	1110	,,	Very fine crystalline showing traces of overheating. Hardened tool steel fracture.	Austenite decomposing. Shows acicular structure. Some fine carbide lines.	
A2B	2	1160	1110	1½	1150	1100	,,	Very fine crystalline with few traces of overheating. Hardened tool steel fracture.	Austenite decomposing. Free carbide in irregular globules and as "lines" and segregations.	
A2Y	2	1170	1090	1½	1135	1100	,,	,,	Almost pure austenite. Very slight decomposition. Carbide lines.	
A3B	1¾	1170	1130	1½	1150	1110	,,	,,	Austenite decomposing. Free carbide as dots and as "lines" and segregations.	
A3Y	2	1155	1100	2	1150	1100	,,	,,	At surface pure austenite. Near centre austenite decomposing. Number of fine carbide lines.	

envelopes had become more laminated and broken up by this forging, whilst occasionally one came across a case, as depicted in Micro 10, of a semi-decomposed austenite.

Rolling from 3½ Inches Square to 2⅛ Inches Square.
(Table IV.)

In all the rolling operations the bars were heated in a coal-fired furnace, being taken out of the furnace at a temperature of approximately 1100° C. The total time taken for rolling was generally less than a minute, about ten passes being carried through in this time. The final temperature after the last pass was in the vicinity of 1050° C.

Microstructures 11 to 13 inclusive show the effect upon the carbide envelopes of this reduction. It is seen that whereas they lack the absolute straightness in direction of the 1⅝-inch and 1¼-inch square and round billets, the extreme curvature existing in the 3½-inch square billets is absent from these, whilst near to the surface the carbide envelopes are almost entirely broken up.

A reduction from 6 inches square to 2⅛ inches square may be looked upon as a critical reduction, a reduction less than this being insufficient to entirely elongate and break up the carbide envelopes, whilst a greater reduction will bring this about.

1¼-inch Square and Round Billets.

After the last operation the bars are either rolled or tilted to 1¼ inch round or square. The data of these operations are shown in Tables V. and VI.

Microstructure of 1¼-inch Square and Round Billets.

As to whether the work has been carried out through the rolls or upon the hammer appears to make little or no difference to the microstructure—the net effect of any reduction, however performed, being to elongate and eventually break up the carbide envelopes.

TABLE IV.—*Rolling from 3⅛ Inches Square to 2⅛ Inches Square.*

No.	Temp. Coming out of Furnace (Scale)	Rolling.						Type of Billet.	Fracture.	Microstructure.	Brinell.
		Total Time.	No. of Passes.	Average Time per Pass.	First Pass Temp.	Last Pass Temp.	Average Temp. drop per Pass.				
	Degrees	Secs.		Secs.	Degrees C.	Degrees C.	Degrees C.				
A1B	1090	50	9	5·5	1040	1020	2	Good	Hardened tool steel fracture. Signs of overheating. Laminations. Remnants of original casting structure.	Austenite decomposing. Carbide envelopes elongated considerably.	
A2T	1090	39	10	3·9	1070 (2nd pass 1100° C. scaled.)	1050	5·5 (from 2nd to last pass.)	„	„	„	
A3T	1110	47	11	4·3	1000 (3rd pass 1100° C. scaled.)	1050	5·5 (from 3rd to last pass.)	„	„	„ Also at ⅛ inch from the surface the "lines" and envelopes show an abrupt change in the amount of distortion which, near the surface, is very great.	
A4B	1130	63 two delays.	11	6·7	1060 (3rd pass 1080° C. scaled.)	1010	6·6 (from 3rd to last pass.)	„	„	As A1B. The decomposition of the austenite is very irregular.	

TABLE V.—*Rolling from 1⅝ Inch Square to 1¼ Inch Round.*

No.	Total Time.	Rolling.				Average Temp. drop per Pass.	Type of Billet.	Fracture.	Microstructure.	Brinell.
		No. of Passes.	Average Time per Pass.	First Pass Temp.	Last Pass Temp					
	Secs.		Secs.	Degrees C.	Degrees C.	Degrees C.				
A1Y	120	15	8	1030	870	10·6	Good.	Very fine crystalline. No trace of overheating. As hardened tool steel.	Austenite decomposing irregularly. Carbide lines which are smaller than the average.	
A2Y	106	18	6	1030	830	11	,,	,,	Austenite decomposing. Carbide lines and segregations.	
A3Y	90	17	5·3	1030	860	10	,,	,,	,,	

TABLE VI.—*Tilting from 1⅝ Inch Square to 1¼ Inch Square.*

No.	First End.			Time to Heat from Cold.	Second End.			Type of Billet.	Fracture.	Microstructure.	Brinell.
	Forging.				Forging.						
	Time.	First Temp.	Last Temp.		Time.	First Temp.	Last Temp.				
	Min.	Degrees C.	Degrees C.	Min.	Min.	Degrees C.	Degrees C.				
A1T	1¾	1100	900	11	2	1110	790	Good	Fine crystalline. Trace of overheating. Similar to hardened tool steel.	Austenite decomposing very irregularly. Carbide "lines" and some segregation. From outside to centre the metal becomes less homogeneous.	
A2B	2½	1110	790	15½	3¼	1140	810	,,	,,	Austenite decomposing. Fine carbide lines and small segregations.	
A3B	2	1100	870	13	2½	1110	850	,,	,,	,,	
A4T	1¾	1060	875	15	1½	1050	850	,,	,,	,,	

Micros 14 and 15 show how completely these carbide laminations are broken up and elongated after a reduction to this size.

Having followed out in detail a series of observations particular to one forging it is unnecessary to dwell at any length upon some of the other operations involved where the mechanical work slightly differs, the tables at the end being self-explanatory and quite simple to follow. Moreover, it is always found that the microstructures of the forgings depend entirely upon the reduction and in no way differ in the rolled or forged bars, providing that the reduction is the same in both cases.

After reducing the diameter to 1¼ inch the bars are subjected to an annealing treatment, which consists of simply heating the bars up to a temperature of 900° C., keeping that heat for sufficient time to soak, slowly cooling to 700° C., and then allowing the bars to cool on the floor. After this treatment they are perfectly soft and machinable, they are then cut to length, and either machined or forged according to the type of tool to be made.

The old practice was to heat up to 800° C. in twenty-four hours, then damp the furnace off from three to six hours, and finally the bars were allowed to cool down during the next thirty-six or more hours. It is thus seen that an annealing which required about three whole days to complete has now been replaced by one which requires at the most only six to twelve hours. The advantage, moreover, of this process of annealing is that it differs from the old one in so much as it refines the structure of the steel, a temperature of 900° C. being above the critical point on heating; it is not therefore, as in other cases, merely a temper annealing.

We have advised this annealing—that is to say, heating slowly to 900° C., then allowing to cool slowly to 700° C.—to replace the previous method of annealing the cast ingots.

During the annealing of the ingot by the old method the cast structure was in no way refined. All that the annealing does is to bring about decomposition of the individual grains, leaving the high crystalline weakness still present in the ingot, whereas, if the ingot were taken above the critical point, breaking down of this cast structure would result, and apart from the persistence of the carbide envelopes, perfect refinement would be brought about. The forged bars are annealed similarly.

After an annealing of this character the bars are shaped first under the hammer, one heat being employed for the purpose, the bars being heated first slowly on the top of a smith's fire, and afterwards put in the hottest part and raised to a temperature of about 1050° or 1100° C. within three minutes. All heavy work is finished when the bar has cooled to 800° C., after which it is inserted in the smith's fire and receives the second and third light shapings on the anvil. This shaping applies only to lathe tools, such tools as milling cutters, twist drills, &c., being machined directly after annealing.

Tables VII. and VIII. refer to rolling and tilting from 2⅛ inches square down to 1¼ inch round and square; reference to the first table will show how these come into the working scheme.

Hardening.

Lathe tools are hardened by the usual method of gradually bringing the tool up to a medium red heat and then putting it into the hottest part of a muffle furnace and allowing the nose to attain a temperature between 1290° and 1300° C.; after this the tool is quickly withdrawn from the furnace and cooled off in the air-blast or in oil, as the case may be.

In the actual hardening temperatures determined, the variations from the ideal were but slight in the tools followed through; the minimum temperature was 1290° C. and the maximum temperature 1330° C., whereas in the case of hardening large drills a minimum of 1240° C. and a maximum of 1290° C. were observed.

The time taken in heating up for hardening was also found to vary but little in each case, the shortest possible time consistent with adequate soaking being employed.

The factors of time and temperature both work in the same direction. High temperature, by promoting greater molecular mobility, will promote excessive grain growth, whilst prolonging the time of heating acts in the same direction. Although high temperature may promote greater solution of the free carbide,

TABLE VII.—*Rolling from 2⅛ Inches Square down to 1¼ Inch Round.*

No.	Temp. Coming out of Furnace.	Rolling.						Type of Billet.	Fracture.	Microstructure.	Brinell.
		Total Time.	No. of Passes.	Average Time per Pass.	First Pass Temp.	Last Pass Temp.	Average temp. drop per Pass.				
A1B	Degrees C. 1050	Secs. 136	18	Secs. 7·5	Degrees C. Missed 5th Pass 1015	Degrees C. 830	Degrees C. 13	Good	Similar to hardened tool steel fracture.	Austenite decomposing. Carbide "lines."	
A2T	1030	79	18	4·5	Missed 2nd Pass 1040	Missed 16th Pass 945	6·6	”	”	”	
A3T	990 Scale Chilled	110	18	6	Missed 2nd Pass 1090	Missed 17th Pass 880	13	”	” (Flaw)	” Decomposition of austenite is very irregular.	
A4B	990 Scale Chilled	101	18	5·5	Missed 2nd Pass 1100	895	12	”	”	Austenite slightly decomposed.	

TABLE VIII.—*Tilting from $2\frac{1}{8}$ Inches Square to $1\frac{1}{4}$ Inch Square.*

No.	Forging 1st End.				Forging 2nd End.					Fracture.	Microstructure.	Brinell.
	Time to Heat.	Forging Time.	First Temp.	Last Temp.	Time to Heat.	Forging Time.	First Temp.	Last Temp.	Type of Billet.			
	Min.	Min.	Degrees C.	Degrees C.	Min.	Min.	Degrees C.	Degrees C.				
A1B*x*	$19\frac{1}{8}$	$3\frac{1}{2}$	1100	750	$27\frac{1}{2}$	3	1080	750	Good	Similar to hardened tool steel.	Ground-mass of decomposing austenite. Carbide lines very fine and drawn out. Close to the surface the lines are broken up.	
A2T*x*	23	$3\frac{1}{2}$	1070	760	22	$2\frac{1}{2}$	1080	830	,,	,,	Ground-mass of decomposing austenite. Carbide lines and several segregations.	
A3T*x*	17	$3\frac{3}{8}$	1060	720	17	2	1080	890	,,	,, (Doubtful signs of overheating.)	Austenite decomposing irregularly; some areas hardly decomposed. Carbide lines which are fairly well decomposed near the surface only.	

Hat.

Time to Black.	rost
Min. Sec.	
2 0	Pure austic amount too
1 30 ...	Austenitic ins free carb ries cont th showing th in taken plac
1 30 ... 1 45 2 0	Pure austenitic size and smll bide as line a
1 45 ...	Pure austenitic Free carbide a Overheated.
1 20 ... 1 30	Pure austenitic Free carbide
1 50 ...	Pure austenitic Free carbide a Somewhat ove time at heat.
1 30 ...	Pure austenitic Free carbide a Overheated.
1 20 ...	Pure austenitic Free carbide a
1 30 1 30 1 30 ...	Pure austenitic size. Free ca lines.

Small crack ground out.

this means should not be used for that purpose, as the result would be large grain growth, whereas even at the high temperature of hardening it was found that massive carbide, if it existed in the tool previous to this operation, was only with difficulty even partially got into solution.

As an illustration of the enormous effect of slight differences in hardening high-speed steels, five micros are shown on Plates XIV. and XV.

No. 16 shows an improperly hardened steel, the temperature not having been high enough.

No. 17 is a steel in the ideal hardened condition; this was hardened at 1300° C.

No. 18 is a steel overheated in hardening. Note the increase in the size of grain. This was hardened at 1305° C.

No. 19 is of a steel hardened at 1310° C. and shows the almost complete absence of free carbide, and how its liquefaction has caused it to resolidify at the grain boundaries with a characteristic eutectic structure.

No. 20 shows a steel hardened at about 1320° C. which has become slightly " crozzled."

No. 21 shows a specimen completely " crozzled " at 1330° C.

All temperatures are actual observations without corrections. It is seen from this that at observed temperatures above 1305° C liquefaction of the carbide begins.

This agrees well with Yatsevitch's work, as published in *Revue de Métallurgie*, 1918, in which he shows from a heating curve that the solidus of a steel of similar composition occurs between 1330° C. and 1335° C., the melting point in heating being 1450° C. Upon cooling from the melt, the same author shows that whereas freezing commences at 1450° C., the metal is not completely solidified until a temperature of 1280° to 1285° C. is obtained.

The effect of this is that this liquid solidifies on cooling again around the boundaries of the crystals as a eutectic. These differences, occurring as they do with slight variation in temperature, are very striking.

The hardening data for a number of tools followed is given in Table IX.

CUTTING TESTS.

A few cutting tests of the steels after being properly hardened were taken. The results of these are given below:

Tool No.	Horse-power.		Feed.	Depth of Cut.	Speed per Minute.	Time to Break Down.
	Light.	Full Load.				
			Inch.	Inch.	Feet.	Minutes.
1	15	40	$\frac{1}{16}$	$\frac{3}{16}$	80	22
2	15	40	$\frac{1}{16}$	$\frac{3}{16}$	80	21½
3	15	40	$\frac{1}{16}$	$\frac{3}{16}$	82	15

The billet used for the cutting tests was not annealed; it was of the following composition:

Carbon per Cent.	Manganese per Cent.	Silicon per Cent.	Sulphur per Cent.	Phosphorus per Cent.	Nickel per Cent.
0·32	0·5	0·114	0·028	0·041	0·22

The test from this material broke at 33·8 tons per square inch.

SEGREGATION OF TOOL STEEL INGOTS.

Series of analyses were taken from the top third of one ingot and from the top and bottom crop ends of two others of those whose manufacture and further treatment had been followed through.

The results are tabulated in Figs. 1, 2, and 3.

Fig. 1 is from the top third of ingot No. 4.
„ 2 „ crop ends of ingots 1 and 2.
„ 3 „ bottom crop ends of ingots 1 and 2.

It will be seen that no segregation—even of carbon, sulphur, or phosphorus—has occurred, and that the tiny carbide segregations which were frequently observed in the micro examinations are not units of large ingot segregations.

The absence of segregation is probably due to two causes: (1) Small size of ingot. (2) Very quick solidification due to the chilling effect of the moulds and to the presence of large quantities of special elements in the steel.

The above-mentioned two causes are in the main the reasons for the almost entire absence of blowholes in these ingots.

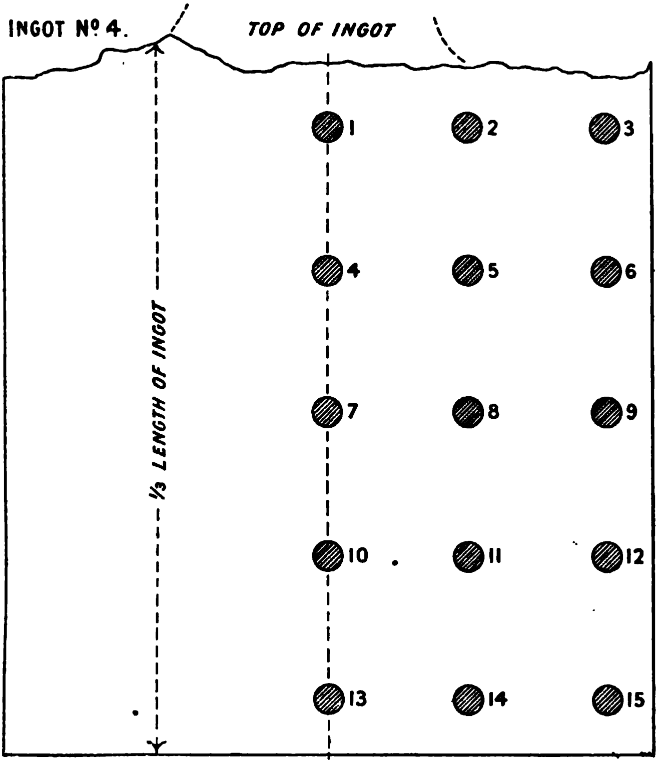

Fig. 1.—Segregation in Tool Steel Ingots.

	C.	Mn.	P.	S.	Si.	W.	Cr.	V.
1	0·60	0·08	0·008	0·060	0·210	13·94	3·77	0·51
2	0·60	0·08	0·010	0·059	0·210	13·98	3·73	0·52
3	0·63	0·08	0·010	0·057	0·200	14·21	3·84	0·51
4	0·58	0·08	0·014	0·060	0·198	14·19	3·84	0·52
5	0·60	0·08	0·015	0·060	0·210	14·16	3·85	0·52
6	0·63	0·08	0·012	0·059	0·198	13·98	3·84	0·52
7	0·61	0·09	0·015	0·058	0·196	14·21	3·89	0·52
8	0·60	0·08	0·010	0·057	0·198	14·08	3·87	0·52
9	0·61	0·08	0·014	0·057	0·198	14·14	3·81	0·52
10	0·60	0·08	0·014	0·057	0·186	14·04	3·89	0·52
11	0·57	0·08	0·012	0·056	0·186	14·16	3·87	0·52
12	0·61	0·08	0·014	0·056	0·186	14·20	3·89	0·52
13	0·60	0·08	0·012	0·059	0·186	13·89	3·88	0·52
14	0·58	0·08	0·004	0·059	0·186	14·00	3·91	0·52
15	0·58	0·08	0·010	0·057	0·177	14·21	3·91	0·52

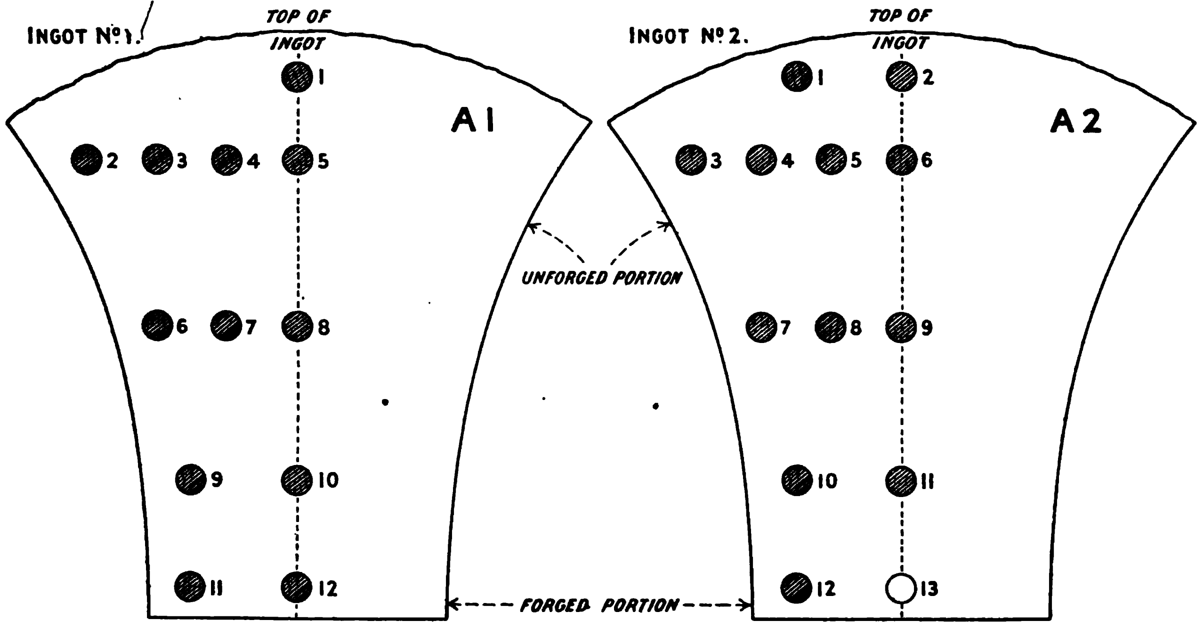

FIG. 2.—Segregation in Tool Steel Ingots. Top Crop Ends after First Forging.

	C.	Mn.	P.	S.	Si.	W.	Cr.	V.
1	0·43	0·08	0·01	0·036	0·177	13·86	3·69	0·48
2	0·60	0·08	0·01	0·037	0·177	14·16	3·88	0·52
3	0·63	0·08	0·01	0·039	0·128	14·17	3·87	0·52
4	0·58	0·08	0·01	0·037	0·140	14·21	3·85	0·52
5	0·53	0·09	0·01	0·041	0·140	14·21	3·82	0·52
6	0·62	0·08	0·011	0·041	0·140	14·25	3·88	0·52
7	0·57	0·08	0·012	0·044	0·140	14·25	3·87	0·52
8	0·61	0·08	0·013	0·044	0·140	14·16	3·85	0·51
9	0·63	0·08	0·01	0·038	0·140	14·25	3·85	0·51
10	0·55	0·08	0·01	0·038	0·128	14·08	3·85	0·50
11	0·62	0·08	0·015	0·043	0·152	14·21	3·88	0·50
12	0·61	0·08	0·011	0·039	0·152	14·08	3·83	0·50

	C.	Mn.	P.	S.	Si.	W.	Cr.	V.
1	0·57	0·08	0·01	0·035	0·152	14·08	3·84	0·47
2	0·57	0·08	0·011	0·036	0·152	13·90	3·82	0·47
3	0·58	0·09	0·011	0·036	0·152	14·17	3·92	0·48
4	0·55	0·09	0·011	0·039	0·140	14·13	3·90	0·48
5	0·60	0·08	0·01	0·042	0·152	14·23	3·90	0·48
6	0·60	0·09	0·01	0·042	0·140	14·77	3·88	0·49
7	0·58	0·08	0·01	0·037	0·140	14·25	3·88	0·46
8	0·59	0·08	0·01	0·039	0·140	14·25	3·90	0·46
9	0·61	0·08	0·01	0·039	0·140	14·21	3·88	0·46
10	0·59	0·08	0·01	0·042	0·140	14·29	3·84	0·46
11	0·58	0·08	0·01	0·042	0·140	14·21	3·87	0·46
12	0·59	0·08	0·01	0·041	0·140	14·29	3·84	0·47
13	0·56	0·08	0·01	0·036	0·128	14·19	3·82	0·45

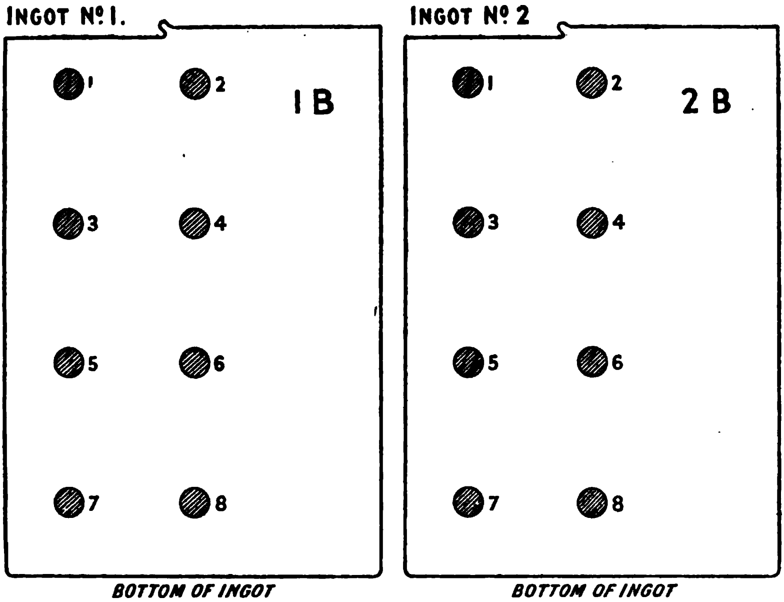

FIG. 3.—Segregation in Tool Steel Ingots. Bottom Crop Ends after First Forging.

Ingot No. I.

	C.	Mn.	P.	S.	Si.	W.	Cr.	V.
1	0·59	0·09	0·015	0·044	0·186	14·16	3·88	0·51
2	0·60	0·09	0·015	0·041	0·177	14·23	3·88	0·51
3	0·61	0·08	0·012	0·042	0·186	14·12	3·90	0·51
4	0·59	0·08	0·012	0·041	0·186	14·16	3·88	0·51
5	0·59	0·09	0·014	0·044	0·198	14·19	3·90	0·51
6	0·60	0·09	0·015	0·041	0·198	14·12	3·88	0·50
7	0·60	0·09	0·016	0·042	0·198	14·12	3·88	0·50
8	0·61	0·09	0·015	0·043	0·198	14·16	3·90	0·51

Ingot No. II.

	C.	Mn.	P.	S.	Si.	W.	Cr.	V.
1	0·54	0·09	0·015	0·043	0·152	14·46	3·87	0·49
2	0·59	0·09	0·011	0·043	0·163	14·08	3·88	0·50
3	0·56	0·09	0·014	0·043	0·163	14·21	3·88	0·49
4	0·57	0·09	0·008	0·044	0·152	14·12	3·88	0·49
5	0·58	0·10	0·009	0·042	0·163	14·12	3·88	0·50
6	0·59	0·09	0·010	0·043	0·163	14·13	3·88	0·48
7	0·58	0·10	0·008	0·044	0·163	14·27	3·88	0·48
8	0·58	0·09	0·015	0·044	0·163	14·08	3·88	0·48

EXPERIMENTS UPON THE ELIMINATION OF CARBIDE LINES.

The chief source of trouble in certain classes of tools, especially large milling cutters, hobs, &c., which cannot receive as much work as, say, a lathe tool or twist drill, is invariably found to be due to the presence of laminated carbide lines. These carbide lines, which are forged out and elongated segregates formed from the melt, are most difficult to eliminate when once formed. The carbide in question is the massive carbide at the boundaries.

If once the carbide be taken into solution and afterwards deposited from the same, it comes out of solution in the form of small dots or nodules, and in this finely divided state is readily taken into solution during the hardening process. Such carbide therefore that comes out upon annealing is in no way detrimental.

An ordinary hardening treatment, owing to the necessity of its being carried out as quickly as possible, is totally insufficient to enable the massive carbide segregates to be disposed of.

A number of experiments were therefore tried in order to determine the effect of a prolonged soaking of a segregated piece of metal at a temperature between 1150° C. and 1200° C. A piece of tool steel was packed in a non-oxidising material in a crucible and heated between these temperatures for a period of six hours; it was then slowly cooled in the furnace, taken out, broken, and half of the piece again put back for another six hours, the same process being gone through, whilst another piece was given a further six hours. Thus the effects of high temperature annealings carried out for six, twelve, and eighteen hours respectively were determined.

The microstructure after these successive treatments presented each time similar carbide boundaries which existed in the original cast structure. After this treatment they were thinner and less massive, but were very sharply defined.

Micros 22 and 23.—The comparison of these micros with Micros 3 and 2 indicate that whilst a certain amount of solution has occurred, this is insufficient to recommend this process. One of the pieces tried became highly oxidised, the fracture of the oxidised bar showing the peculiar structure depicted in Photo No. 24.

This fracture consisted of very large bright crystals with one axis longer than the other, the longer axis being normal to the surface, whereas the central core consisted of fine equiaxial crystals.

Upon polishing this section it was noticed that the core stood out in relief above the rest of the metal, an indication of the hardness at the centre. Etched with nitric acid a peculiar macrostructure resulted which is shown in Photo No. 25.

This macro shows all the characteristics of the fracture. The outside ring consisted of very large grains, the boundaries of which were often skirted with well-developed pearlite, the grains themselves consisting of a homogeneous light etching material, ferrite, in which are embedded a number of massive carbide segregates.

The large grains end abruptly at the pearlite boundary which totally encloses the central core, the latter part consisting of pure austenite and massive carbide.

The interesting points with regard to this decarburisation are, firstly: that the decarburisation gradient is very steep at the pearlite boundaries; that this pearlite boundary, which is very thin, is a distinct line of demarcation between the almost carbonless and completely softened steel and the austenite. The massive carbide resists decarburisation better than any other of the structural elements. It is obvious that ordinary tool steel is of a decidedly hypereutectoid nature.

BRINELL HARDNESS OF A.W. STEEL.

The Brinell hardness was measured after each operation in the manufacture of the tools, and the results condensed in the following table:

Operation.	Brinell.			Number of Determinations.
	Average.	Highest.	Lowest.	
After annealing ingot	259	262	255	16
,, cogging to 3½ inches square . .	540	600	505	19
,, rolling from 3½ inches to 2⅛ inches .	604	652	555	9
,, cogging from 3½ inches to 1⅝ inch .	610	562	600	15
,, tilting to 1¼ inch square . . .	616	652	600	18
,, rolling to 1¼ inch round . . .				
,, annealing	249	269	231	12
,, hardening	652	...	...	...

It will be noted that with decrease in cross-section there is a corresponding increase in the Brinell hardness number.

HEATING AND COOLING CURVES OF A.W. STEEL.

On Fig. 10 will be found a heating curve followed by a series of cooling curves of A.W. steel taken from different temperatures and with varying rates of cooling.

Heating Curves.—Two points are shown, a small one with a maximum at 775° C., and a larger one (maximum 850° C.). The exact significance of the lower point has not yet been determined.

A steel when heated and quenched above the lower point reveals no alteration in hardness, the value obtained being 231, which is that of the annealed steel. The microstructure is represented by Micro No. 27. This micro differs from that of the annealed steel, Micro 26, in that the ground-mass contains a considerably greater proportion of smaller white dots.

The upper point, maximum 850° C., appears to be similar to the ordinary Ac3,2,1 change, the temperature of this change being raised very considerably by the combined presence of tungsten and chromium.

A steel quenched above the upper point on heating, namely, 880° C., has a hardness of 532, and a microstructure similar to No. 28. This structure, although similar in appearance to that of the annealed steel, is totally different. The white blobs of separated carbide, one must assume, are the same in both cases. The matrix in this case, however, is martensitic.

Cooling Curves.—Cooling from an initial temperature of 914° C. one large evolution of heat is shown at 764° C. The change from the hard to the soft state is so complete in cooling from this temperature even at a moderately rapid rate that the hardness has been reduced to 241.

Cooling from an initial temperature of 1032° C. the critical point is depressed to 407° C.; this depression progresses slightly with the maximum initial temperature until at a temperature of 1300° C., with very slow cooling, a very large evolution of heat is obtained at 380° C. The variation in hardness with increasing temperature is rather remarkable. With an initial

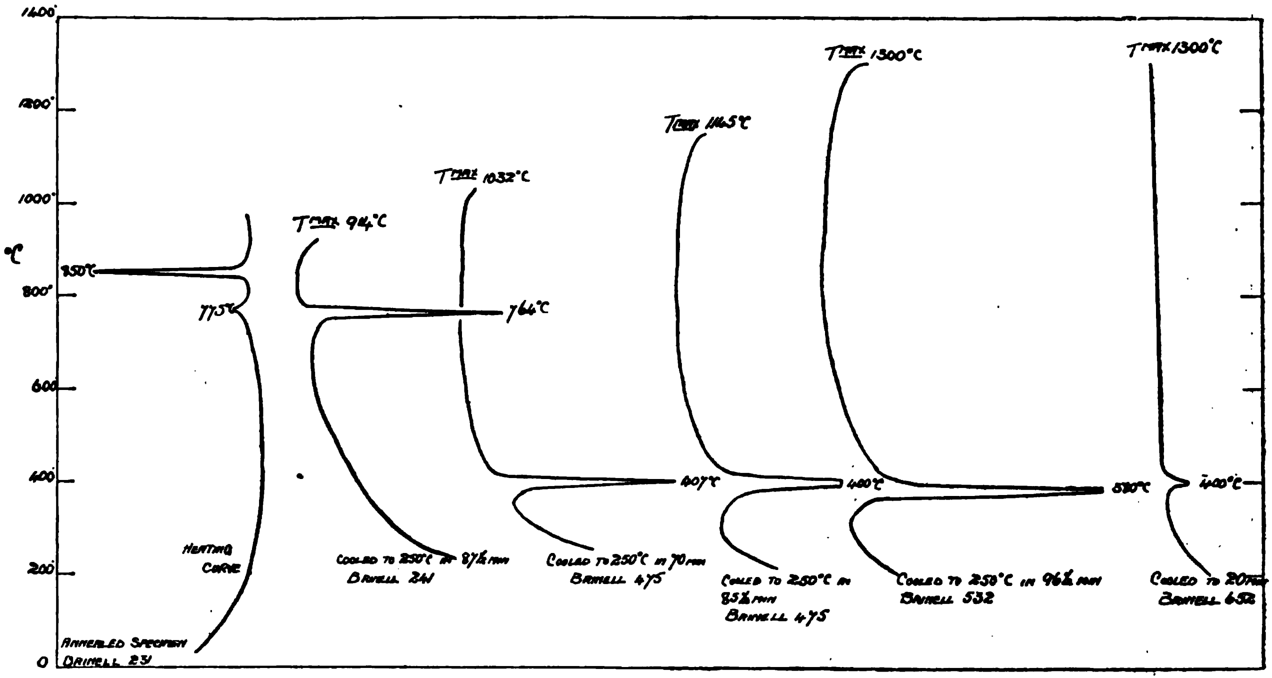

FIG. 10.—A.W. Steel. Heating and Cooling Curves.

temperature of 1032° C. and also of 1145° C. with furnace-cooled specimens the Brinell figure was 475. With an initial temperature of 1300° C. slowly cooled (ninety-six minutes) the hardness figure jumped to 532.

If we compare the steels cooled from 1145° C. and 1300° C. respectively, we note that although the latter presents a larger evolution of heat at the critical point, the resulting product is harder. This can only be accounted for by assuming that a definite chemical or physical change takes place in the metal at the high temperature, with the result that the product deposited as the steel passes through the recalescence point, or the remaining solution, is harder than in the case of the steel cooled from 1300° C.; that is to say, there must be some radical change in constitution between the temperature of 1145° C. and 1300° C. This agrees with Yatsevitch, who found that the higher the initial temperature, the larger the evolution at the critical point and the greater the hardness.

With a moderately rapid cooling from 1300° C. a small point is observed at 400° C., whereas if air-blast is employed a curve free from all critical points is obtained. This represents the rate of cooling that should be attempted in practice. A steel quenched from 1300° C. has a structure shown in Micro 29, which is similar to that of a steel quenched in the air-blast.

Annealing Treatment.

As before mentioned, the system adopted in the works for the annealing of tools occupied about three days' time. It was obvious, however, after taking a cooling curve from 914° C. and measuring the resulting hardness of the specimen, which was 241, that a far quicker and simpler treatment might be employed to produce the same effect. Accordingly specimens of about 1 inch square of A.W. steel were taken, and in order to get them in a state similar to that of the ingot or forging, they were air-hardened to 1300° C. It is true that this treatment would rather exaggerate the nature of the case, but the exaggeration is on the right side, so that any treatment which would bring about softening of these specimens would have a similar effect on those in practice.

The following table summarises the experiments:

Max. Temp.	Time at Heat.	Time Cooling to 740° C.	Brinell No.
Degrees C.	Hours.		
945	½	1½ hour.	302
940	nil	½ ,,	475
935	½	1½ ,,	269
900	½	1½ hour. Water quenched.	255
		,, Air cooled.	253
		,, Furnace cooled.	243
		,, Very slowly cooled.	248
870	½	1 ,,	269
860	nil	20 minutes.	302
800	½	Water quenched from 800° C.	340
	1	Furnace cooled.	321
	1½	,, ,,	302
	2	,, ,,	293
	3	,, ,,	287

The aim of these experiments was to take the steel to a temperature slightly above the critical point on heating, and to avoid taking it to a temperature which would produce any self-hardening, which occurs when the maximum temperature is such that a recalescence at about 400° C. begins to show.

It is seen from the table that a temperature of 950° C. is the maximum limit to which the steel can be heated in order to bring about complete softening. The maximum that should be employed in practice to give the best results is 935° C., whilst the minimum to effect the same is 870° C.

Experiments carried out at a temperature of 800° C., which is similar to that employed in practice, show that even after four hours' soaking at this temperature, the softening was not so pronounced as that produced by half an hour's soaking at 935° C. or 870° C.

All that is necessary, therefore, is to heat the bars up to between 870° C. and 935° C., thoroughly soak at this temperature, and cool off within about one hour to 740° C., when complete softening will have been brought about. After this the bars may be pulled out and cooled quickly in air.

SECONDARY HARDENING.

Some experiments of the type carried out by Prof. Edwards upon secondary hardening treatment gave the results shown in

Fig. 4. The full line indicates hardness after various tempering temperatures, the initial hardening being carried out at 1300° C.

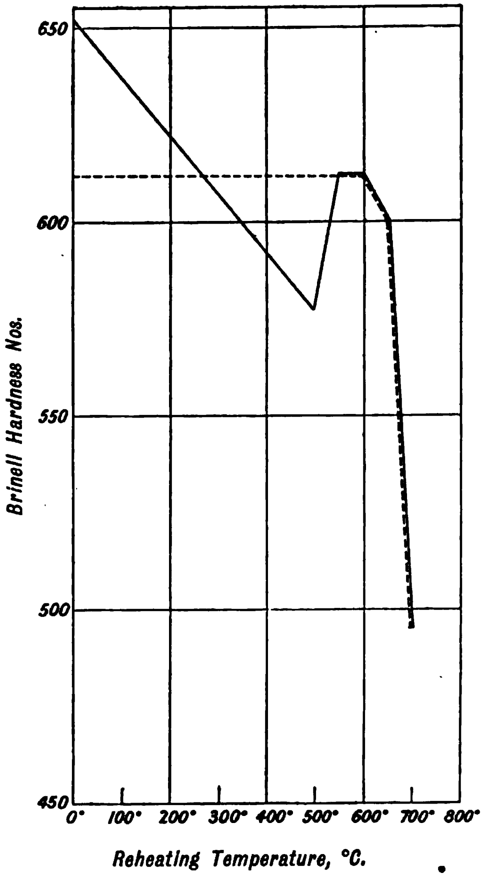

Fig. 4.—Secondary Hardness of A.W. Steel.

——— Steel hardened before secondary treatment experiments.
– – – – ,, ,, and heated to 600° C. for ten minutes before secondary treatment experiments.

The usual minimum is seen at a temperature of about 500°C., rising to a maximum between 550° C. and 600° C. The dotted line shows the effect of tempering at various temperatures after hardening and a preliminary secondary hardening carried out at 600° C.

It is thus seen that the effect of secondary hardening, although it lowers the initial hardness of the specimen, does increase the stability of the steel. After this treatment the hardness remains constant throughout up to a temperature just above 600° C.

FAILURES IN TOOLS.

Failures arise in tool steel due to various causes. Some may be traced back to faulty casting, others to faulty rolling, and also to faulty hardening.

As regards carbon steels, faults in general have been thoroughly treated by H. Brearley in his numerous text-books, not so fully, however, with regard to high-speed steels.

Failures due to Casting Conditions.—If too high a casting temperature is employed a highly dendritic structure will result. This structure, which is naturally weak, cannot be afterwards obliterated either by heat treatment or even mechanical work.

Micro 30 shows a typical case of dendritic structure occasionally found in a faulty tool. In these it is seen that the dendrites are very clearly developed and form beautiful fir-tree crystal skeletons. There is no need to dwell upon the statement that this structure is mechanically weak.

Failures due to Segregation.—Although the analyses previously given from all parts of an ingot show that practically no segregation occurs in tool steel, the authors have come across one case where this did occur. Micro 31, taken at 5 diameters, shows a large segregation right in the centre of the nose of a twist drill. This segregation, which was harder and more brittle than the surrounding metal, naturally was the cause of failure of the tool.

Failures due to Slag.—The occurrence of slag and manganese sulphide is very rare in tool steel; occasionally, however, they are met with.

Casting Phenomena which are accentuated by Mechanical Treatment.—Micro 32 shows a small roak developed by forging. The crack which was therefore originally in the ingot has been distorted and extended by forging.

Micro 33 shows rather a different case of crack, this being more in the nature of what is generally termed a forging crack. Here it is seen that the crack is filled, not purely with oxide material, but also with slaggy material picked up in the furnace during heating up for forging, the forging process squashing this in, as it were, and slightly extending the crack.

Carbide Segregations.—These are undoubtedly the most troublesome features that arise in tool steel. They usually only occur in the case of tools of such large size as to permit little forging to be put into them. Micro 34 shows typical laminated carbide lines, which have not been obliterated and pulled to pieces by the forging treatment. They are of the noted hook or crook shape so detrimental to tool steel. It should also be noted in passing that this tool had been hardened at an excessively low temperature, shown by the composite structure of the matrix.

Sometimes these carbide segregations exist as envelopes around the grains. This indicates even less drastic forging than the former case.

Carbide out of solution in steel in any form other than small specks is invariably found to be detrimental.

Micro 35 shows a rather curious case of a crack running through the steel in no particular direction—that is to say, its course is not determined by the grain boundaries or carbide envelopes. Cracks of this nature are occasionally found in a steel, of which this is a typical example, which has not been hardened at a sufficiently high temperature, the metastability of a semi-hardened structure being far greater than that of a properly hardened structure, the nuclei of the stable phase creating a tendency for a volume change to take place in the metal which will cause a crack.

Micro 36 is added merely for interest. It represents the longitudinal section of a shaving of a 0·35 per cent. carbon steel about $\frac{3}{16}$ inch thick, which was taken off during the cutting tests. The distortions formed by the ferrite are clearly visible in the photograph, which shows the usual effect of strain of this character.

SUMMARY AND CONCLUSIONS.

The whole process of manufacture of high-speed steel has been followed through, and it must be admitted that greater uniformity of working is hardly possible.

As far as casting is concerned some slight improvement might be made by increasing the thickness of the mould walls and lowering the pouring temperature of the metal.

An investigation of the various forging operations of cogging, rolling, &c., has been made, and it has been found that, for efficient forging, temperatures must be used which are appreciably higher than those generally accepted as correct.

It is also shown that whether reduction is effected by rolling or hammering, or a combination of both, there appears to be little or no difference in the microstructures.

What is, however, of the utmost importance is the amount of reduction in forging which the metal undergoes between the cast state and the finished bar.

Micros taken after various processes of forging and rolling indicate that below a reduction of 88 per cent. for a 6-inch ingot, the distorted carbide envelopes occur in the form of loops and hooks of various configurations, and it is in this form that they are most dangerous. This is a point emphasised by Brearley in his book on tool steel.

Finished milling cutters which have broken in use owing to carbide laminations invariably show the laminations to be in this form. If the laminations are discontinuous and broken up they seldom give rise to trouble. From this we must conclude that the reduction should even go beyond this figure. For large tools, therefore, it is desirable to cast a larger ingot and to put more work into the steel.

Experiments have shown that carbide in the finely separated state can be readily made to go into solution at a sufficiently high temperature. If, however, it occurs in the massive form as in the carbide envelopes or laminations, it is almost impossible to bring this about, as has been shown by the experiments mentioned, namely, by high temperature soaking.

With regard to annealing treatment, all that is necessary to bring about complete softening of the steel is to heat the steel just above its higher critical point on heating, and slowly cool down through the point on cooling.

Hardening times and temperatures are of the utmost importance. Grain growth in high-speed tool steel is certainly slow when compared with carbon steel at low temperatures, but at the high hardening temperatures it is rapid enough to give rise to a very coarse structure even with an increase of 20 per cent. in a hardening time of 2½ minutes.

The temperature limits for really efficient hardening are as narrow as 10° C. Hardening should be carried out between the temperatures of 1300° C. and 1320° C. (corrected temperatures). If the temperature is above 1320° C. overheating and finally burning will occur, whereas, if below 1300° C., an insufficiently hardened steel will result. In either case defective tools will result.

The cooling curve data agrees very well with similar determinations made by Yatsevitch.[1] On the basis of his freezing curves the burning of the tool steel when heated above 1330° C. is readily explained.

The various defects occurring in high-speed steel have been reviewed and commented on. The greatest troubles are due to the insufficiently distorted carbide envelopes and incorrect hardening.

The authors wish to express their thanks to Messrs. Sir W. G. Armstrong, Whitworth & Co. Ltd., and especially to Mr. F. B. Trevelyan, for their kind permission to publish these results, also to Mr. E. F. Law for the interest he has taken in the work. They are likewise indebted to Mr. W. R. Dyson for his valuable help throughout.

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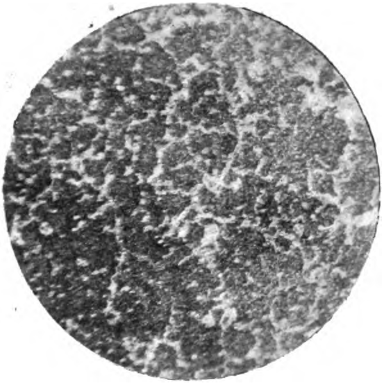
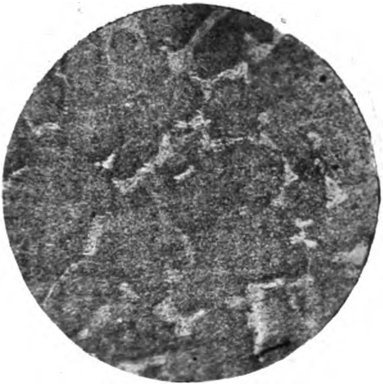
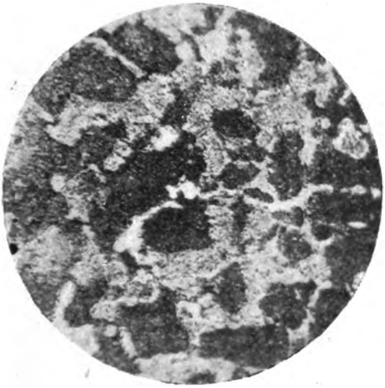
[1] *Revue de Métallurgie*, vol. xv. pp. 65–115, 1918.



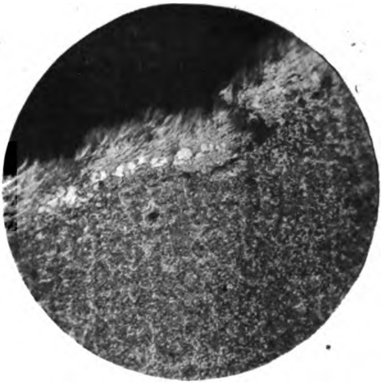
No. 1.—Near surface. × 200.



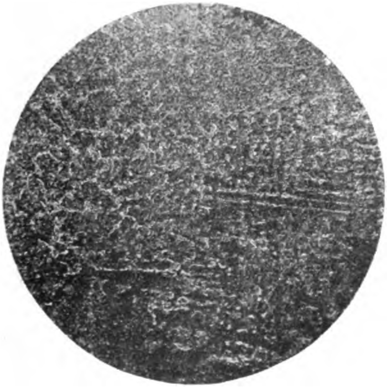
No. 2.—1 inch in from surface. × 200.



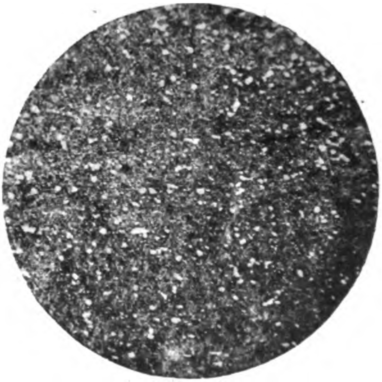
No. 3.—Carbide segregation near centre of ingot. × 200.



No. 4.—Extreme edge of ingot. × 200.



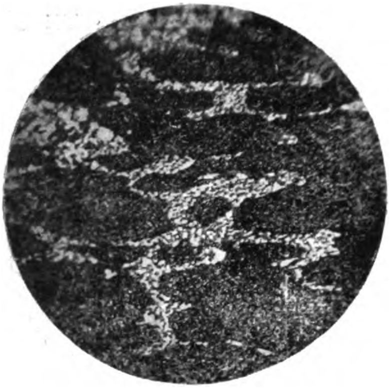
No. 5.—From near edge of ingot showing dendritic structure. × 200.



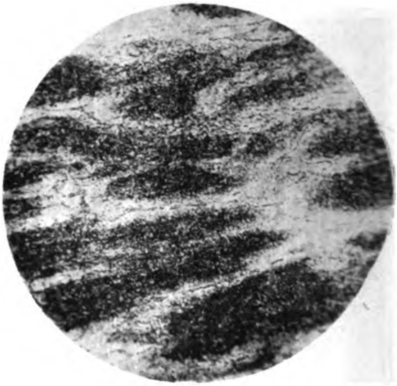
No. 6.—Near surface. × 200.

Al reduced by one-third.

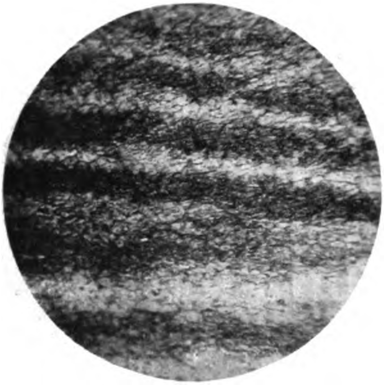
To face p. 386.



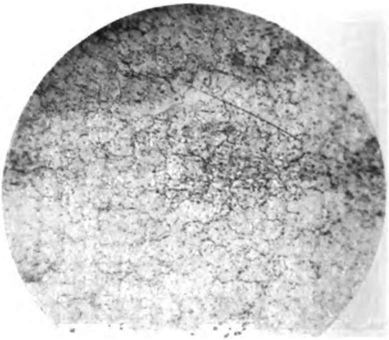
No. 7.—Distorted carbide segregation. × 200.



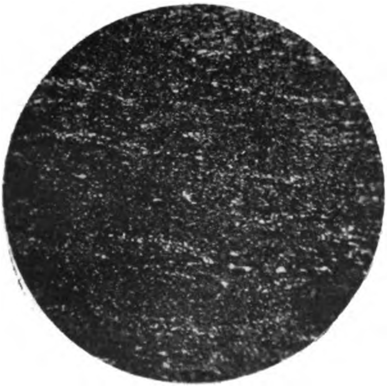
No. 8.—Distorted carbide envelopes. × 200.



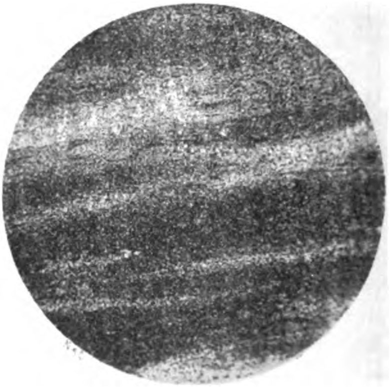
No. 9.—Showing lamination of carbide envelopes. × 200.



No. 10.—Showing semi-decomposed austenite. × 200.



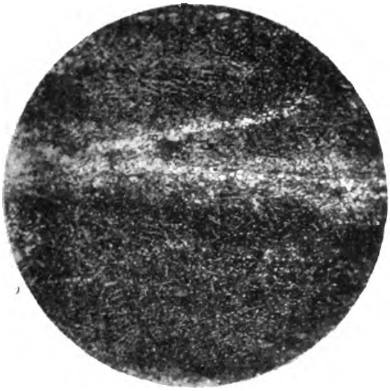
No. 11 —Near surface of billet. × 200.



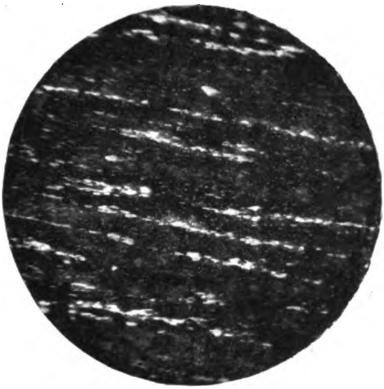
No. 12.—Half way in. × 100.

All reduced by one-third.

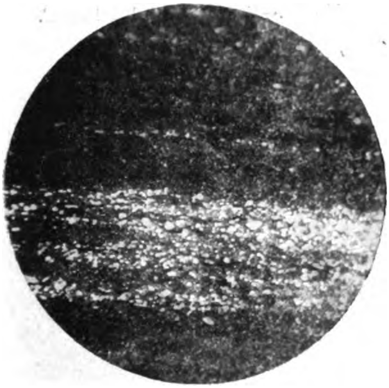
PLATE XIV.



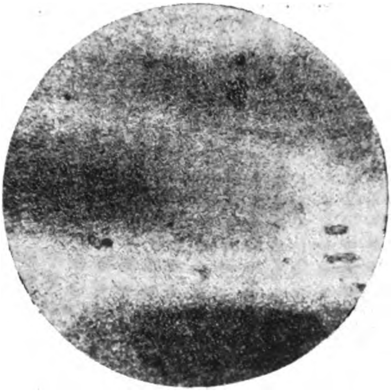
No. 13.—Near centre of billet. × 200.



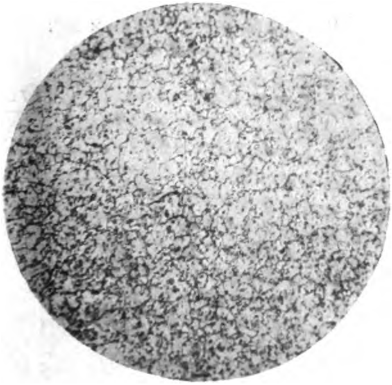
No. 14.—Final arrangement of carbide envelopes. × 200.



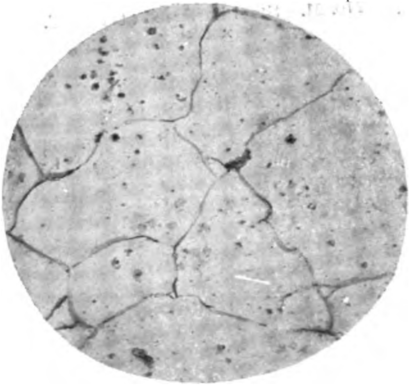
No. 15.—Final arrangement of carbide segregation. × 200.



No. 16.— Improperly hardened steel. Temperature not high enough. × 200.



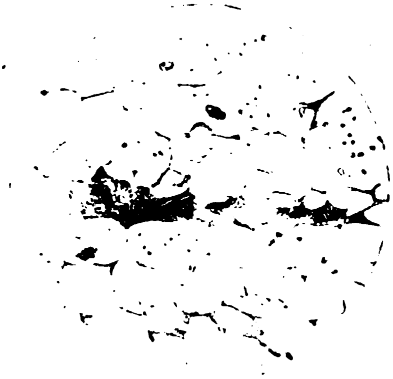
No. 17.—Ideal hardened condition. Temperature 1300°C. × 200.



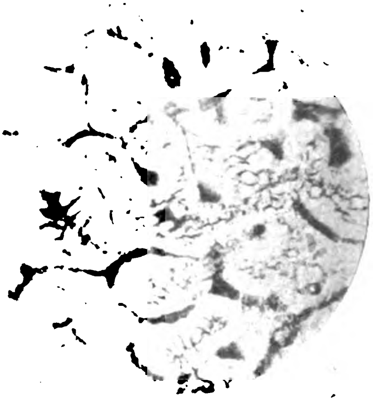
No. 18.—Overheated in hardening. Temperature 1305°C. × 200.

All reduced by one-third.

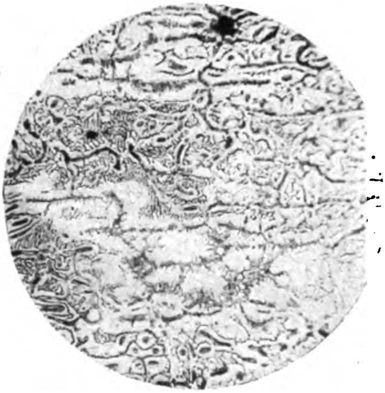
PLATE XV.



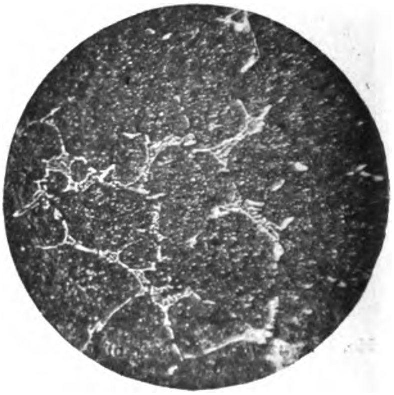
No. 19.—Steel hardened at 1310°C. × 200.



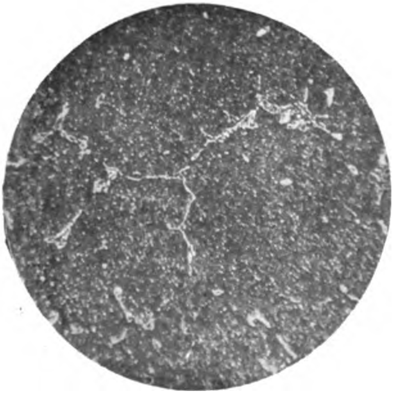
No. 20.—Steel hardened at 1340°C. × 200.



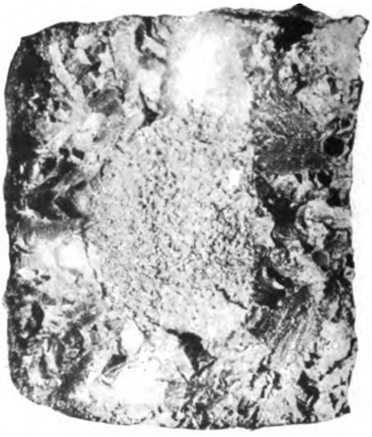
No. 21.—Steel hardened at 1350°C. × 200.



No. 22. × 200.

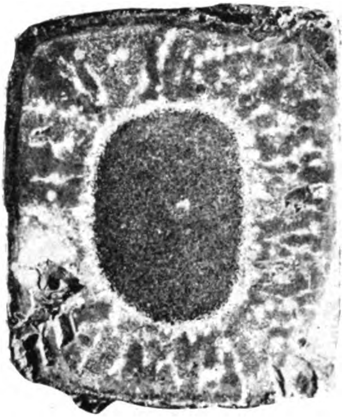


No 23.—Effect of prolonged soaking at 1150° to 1200°C. of segregated piece of tool-steel. × 200.

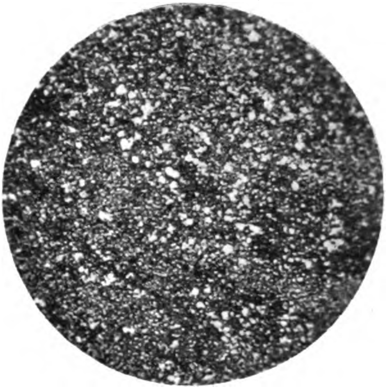


No. 24.—Fracture of bar. × 8.

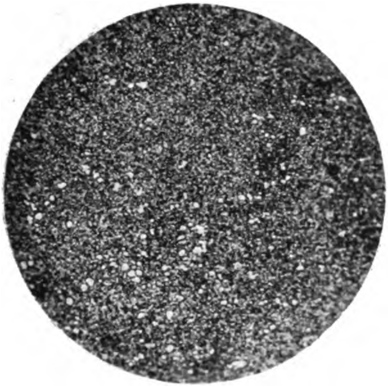
All reduced by one-third.



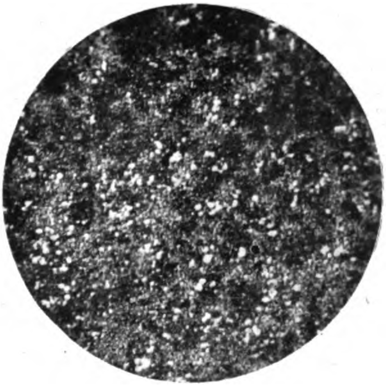
No. 25.—Macrostructure after etching with nitric acid. × 8.



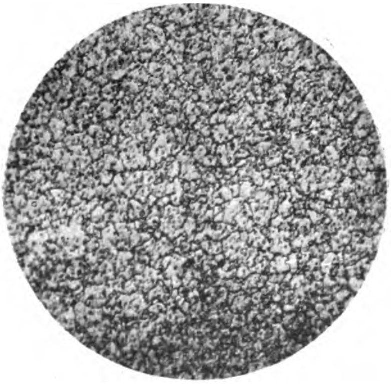
No. 26.—Annealed. × 200.



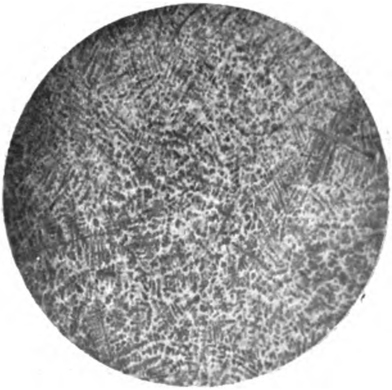
No. 27.—Water quenched from just above the lower point. × 200.



No. 28.—Water quenched from just above the higher point. × 200.

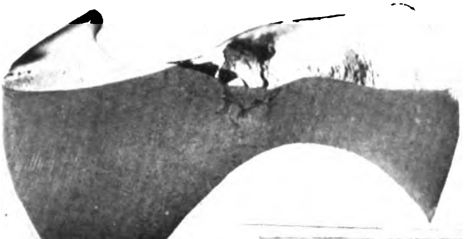


No. 29.—Water quenched from 1300°C. × 200.

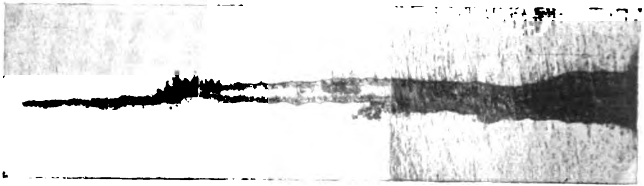


No. 30.—Dendritic structure found in faulty tool. × 4.

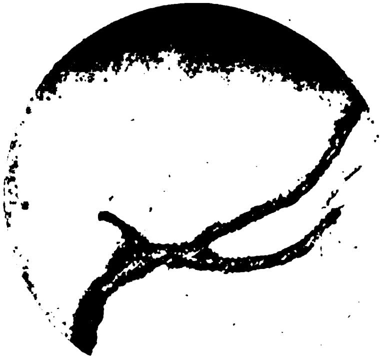
All reduced by one-third.



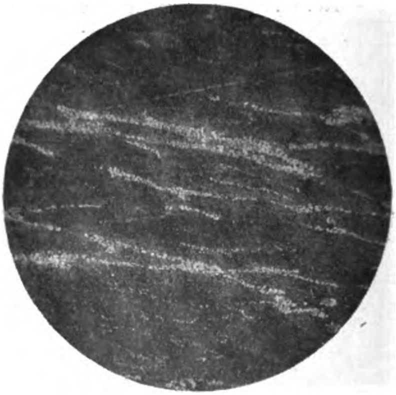
No. 31.—Showing segregation in centre of nose of twist drill. × 2.



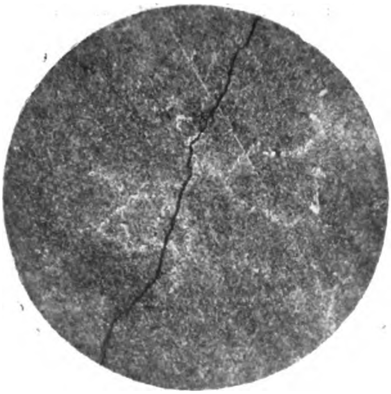
No. 33.—Showing forging crack. × 20.



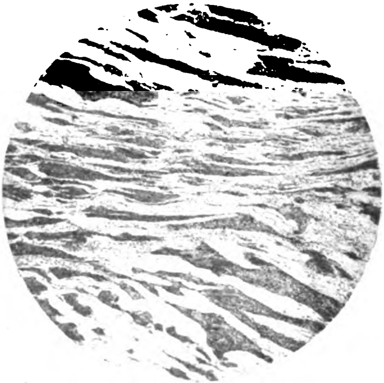
No. 32.—Showing small roak developed by forging. × 20.



No. 34.—Showing typical laminated carbide lines not obliterated by forging. × 100.



No. 35.—Typical case of crack in steel hardened at an insufficiently high temperature. × 100.



No. 36.—Longitudinal section of 0·85 carbon steel shaving. × 100.

Figs. 31 and 33 reduced by one-half; Figs. 32, 34, 35 and 36 reduced by one-third.

To face p. 337.

DISCUSSION.

Professor H. M. **Howe**, Honorary Vice-President, said he thought the members must be deeply gratified at the extremely frank way in which a valuable practice had been disclosed. It appeared to him that the paper was typical of the times. Everyone felt that we must all pull together and help each other. We had passed through a terrible period and our civilisation had nearly been swept away, and during that time we had interchanged information very freely, so that the least efficient might be brought up as nearly as possible to an equality with the most efficient. He thought everyone would welcome the sign that that spirit was persisting. The imponderables were much more important than the ponderables, and the paper could not be welcomed too warmly. With regard to the question of the size of ingots, there was an impression that increasing the size of ingots was to be guarded against, that the difficulties of segregation, the dendritic segregation, were increased far more by increasing the size of the ingot than the corresponding effacement of that inter-dendritic segregation by the increased degree of reduction in rolling. Many years ago tire-makers had started making tires from large ingots, but they had gone back to single-tire ingots. In Pennsylvania there was a magnificent slabbing-mill for making boiler-plates, which he believed cost about 1,000,000 dollars at pre-war prices. To-day the mill was not in use, because it was found better to cast single-plate ingots or small ingots, chiefly for the reason that the larger ingot and the slower solidification gave rise to the greater inter-dendritic segregation. In the manufacture of cannon in America they had greatly reduced the amount of reduction from the ingot to the cannon, and he believed all the indications pointed in that direction. It could not be forgotten that the best steel, crucible tool steel, was made in very small ingots. Whether that was done through wisdom or whether it was stumbled on and it was discovered that the steel made in those small ingots was better than that made otherwise, he did not know, but it was well known that many firms had experimented at very considerable expense in using large crucibles and pouring several crucibles into a given mould. He did not know anywhere in America where that had persisted. They had gone back to the point from which they had departed, the small ingot of crucible steel

Prof. C. A. **Edwards** (Manchester University) wished to associate himself with the remarks Dr. Howe had made, and also to thank the firm with whom the authors were associated for permitting them to publish such valuable results. It was often very difficult indeed to get a detailed account of such practical information. In regard to the difficulty of oxidising the special carbides, he could endorse what Dr. Andrew had said. He had endeavoured to make chromium steels and chromium tungsten steels almost carbonless by the ordinary process of decarburisation, but it was absolutely impossible to eliminate carbon in that way. The authors stated that if they compared the steels cooled from 1145° C. and 1300° C. respectively, they noted that, although the latter represented a larger evolution of heat at the critical point, the resulting product was harder. Later on they said that there must be some radical change in constitution between the temperature of 1145° C. and 1300° C., and that that agreed with the observations of previous workers. When those curves were referred to it was evident that the information given was insufficient to enable the matter to be dealt with. It was, however, known that the apparent magnitude of a critical point was a function of the rate of cooling, and that, in order to compare the question of whether a given critical point on a curve was larger than another, it was necessary to know exactly the rate of cooling during the change. In the three curves from left to right, in which direction the point appeared to increase in magnitude, there was a slowing up in the rate, so far as could be judged from the data given, which would tend in the direction of increasing the apparent magnitude of that critical point. He did not dispute the possibility of the authors' view being correct, but it would be better if they could support it with more definite evidence. It was quite possible that with certain rates of cooling with certain alloy steels the kind of carbide would be different than if an entirely different rate of cooling were adopted. Perhaps if a concrete example were considered it might be possible to have, say, iron carbide coming out of solution when the rate of cooling was slow, and then another more stable compound, say chromium carbide, being formed. The first reaction might be exothermic and the second endothermic, so that the net result would be a lower thermal effect than the ordinary iron carbide change. Under those conditions if the rate of cooling were progressively increased it was possible that the endothermic reaction might be cut out, in which case the thermal magnitude would be greater as the rate of cooling increased up to a certain point. Of course to get information in that direction it was necessary very carefully to consider the rate of cooling and to determine the area of the peak. With regard to the secondary hardening, he was rather pleased that the authors had confirmed his (Prof. Edwards') observations. The authors found that the secondary hardening persisted when the steel was again reheated up to about 600° C., for they did not get the dip in the curve at the intermediate temperature. As a matter of fact he certainly would not have expected any such dip, but he was rather pleased the authors had made the experiment.

Mr. H. H. Ashdown (Newcastle-on-Tyne) wished to express his appreciation of Dr. Andrew and Mr. Green's valuable and interesting paper. The paper made it quite clear that Manchester was holding its own in the manufacture of tool steel. He remembered some years ago Mr. Gledhill, when discussing the manufacture of that material, spoke of it as being carried on in a little back street. When he (Mr. Ashdown) became associated with the firm a few years ago he was astonished to find the magnitude of that little back street, and how valuable the work that had been done there. The authors said they noticed no difference between the microstructure of rolled and of hammered steel. Microstructure explained a good deal, but often it was somewhat misleading—like melting furnace gases, which often gave the same analysis even when the properties were very different. Had the authors carried out any machining tests with both rolled and hammered bars? He was disposed to think that the hammered bars would stand up to their work for a longer period. The authors stated that the carbide could only be broken down by ample mechanical work, and one was led to understand that the mechanical work must be all in a longitudinal direction He would like to know whether in making milling cutters, if the ingots were partially longitudinally forged and then the piece up-ended and well hammered out in the reverse direction, so as to get the necessary diameter, that carbide was also broken up. With regard to the work being permitted by the firm to be brought before the Institute, in speaking of a firm one always had some individual member in mind. He thought the member in the present case was Mr. Trevelyan, who had always done his best to encourage the distribution of scientific knowledge not only in their own works but to any others requiring such assistance or advice.

Dr. W. H. **Hatfield** (Sheffield) thanked the authors for their very interesting and accurate statement of works practice. He thought the pyrometric readings through the process would prove of very great interest to many people. As Dr. Rogers had pointed out, it was their own practice in Sheffield to do similar work. He (Dr. Hatfield) questioned the authors' suggestion that the white constituent was carbide of iron. Taking into consideration the investigations that had been carried out of late, particularly those of Arnold and Ibbotson, and having in mind also other investigations by Prof. Carpenter, Drs. Edwards and Swinden, there had been a lot of work done on the constitution of steel containing a high percentage of tungsten, and he thought the evidence pointed to the white constituent being tungstide and not carbide. Dr. Andrews himself pointed out the possibility of that, but in the paper it was simply spoken of as carbide. It was highly important, because, as the authors pointed out, that constituent, whatever it was, was undoubtedly the seat of a good deal of trouble in high-speed steel, not only in the particular fairly low tungsten chromium steel dealt with, but also in the more recent high-speed steels which were now being produced. He thought it would be useful therefore fully to discuss the question of what the white constituent was.

Mr. C. G. CARLISLE (Sheffield) said Sheffield seemed to be challenged by Manchester, but he did not know why that should be so, seeing that Sheffield sold steel to Manchester people, and sometimes had to go and heat-treat it for them. He had had to do so some little time ago, helping with a turning tool which was being heated up for hardening in a very small and rather crude muffle furnace, not heated up to a sufficiently high temperature, and giving a rather poor result, although they were working on a very hard cast iron face-plate with slots in. He improved their results and subsequently did some hardening in Sheffield and sent them the tools with which they got better results. The authors' Table I. gave a casting temperature of 1410° C. to 1440° C. in the pots, and then in pouring it into the ladle one of 1330° C. to 1340° C. Those tables of temperatures did not appear to him to be very helpful because they were a long way from the truth, nor did they recommend the optical pyrometer as an instrument for measuring casting temperatures, as they seemed to make no clear distinction between the 1330° casting temperature and 1330° hardening temperature. He did not know that high-speed steel was cast at the same temperature that high-speed tools were hardened at. The casting temperatures were optical ones and needed a good deal of correction. The authors conveyed the impression that they were approximate. They could hardly even be that. They must be more than 200° out, otherwise the steel would never have been got through the ladle nozzle. The authors had rather taken the sting out of any criticisms on the hardening temperatures by their corrections, although the photomicrographs Nos. 17 and 18 were still left uncorrected. There was a difference made between 1300° and 1305°, the first temperature giving an ideal hardened condition and the second temperature an overheated structure. He did not know whether those were taken on the same bar, but there seemed to be a larger range, in actual practice, than only 5° difference between an ideal and an overheated steel. Whether it was carbide or tungstide he was not prepared to say, but it seemed to him in dealing with the photograph of a drill (Fig. 31) and also with the segregation of the ingot, which persisted right through to the finished bar, no matter what size it became, to be a very practical problem, because the centre of the ingot became the centre of the drill, and if there were central segregation the chisel point of the drill would be involved. A good deal of trouble might arise through that segregation in drills, although it would not affect turning tools, because in that case it was not a question of the centre of the bar being involved. So far as his work went, segregation was more marked in crucible steel, and in electric steels it was less so; he would say probably one-half or one-third in amount. He was rather surprised that electric steels had not been studied by the authors, but perhaps in a subsequent paper they might take them up, as they were well worth studying in respect to segregation. With regard to cutting tests in high-speed steels, crucible and electric, the best results he had obtained so far were with electric steel, and the range of hardening and subsequent tempering was far greater in electric steel than in crucible steel. With regard to the drill point, he did not suppose the segregations given by the authors were carbide segregations, to which they referred in another part of the paper. They must be chemical segregations that would respond to analysis. Making larger ingots, as suggested by a previous speaker, would not cure segregation trouble. In forging and rolling down to ¾-inch bars, there would still be found the same relationship of segregation practically unaltered. Even small contraction cavities which were generally found in crucible high-speed steel persisted in a ¾-inch area, just as in 4-inch or 2-inch square bars, and occupied much the same position though considerably reduced in size. With regard to the softening process, he had used a similar temperature—he had tried 780° not 700°—and found it occupied much less time to soften than the old method of heating up gradually to 850°, soaking for a time and cooling very gradually. He wished it to be understood that his remarks embodied his own personal views.

Dr. F. Rogers (Sheffield) said that, without wishing in the slightest degree to detract from a most valuable paper, something was known of the subject in Sheffield. If, however, Sheffield did not talk about it somebody else would, as for example the authors had now done. He wished to emphasise the importance of the question of rapid annealing raised by the authors. In certain Sheffield works, as a result of investigations with which he had been connected, a very similar process had successfully been adopted for some years, to the exclusion of the old very slow cooling process. The Brinell numbers given by the authors on p. 331 were still rather high for the rapidly annealed material, but the other special factors for those samples taken together would no doubt help to elucidate the point and possibly lead to lower values in future trials. There could be no doubt that there were enormous variations in results in the hardening of high-speed steels, which sometimes seemed almost inexplicable. Such results were brought out not by the Brinell test, but by cutting tests. It was possible to treat two tools simultaneously and yet very rarely get the same results. A method which he, in association with others, had used was to break a piece of bar in two, form a tool nose on each piece next the break (by grinding, in the case of investigations), and put the two pieces together, with their noses in contact, in the furnace. Variations might even then be of the order of 25 per cent. It was a difficult thing, in the hardening of high-speed steels, to control the treatments and measure the temperatures sufficiently accurately in all relevant respects

Mr. Howard J. Stagg, Jun. (Syracuse, N.Y., U.S.A.), said that before leaving America he had been impressed by what his friends had told him of the conservatism of the English steelmaker. His surprise and pleasure might therefore be imagined upon finding such an able paper dealing with works methods as that under discussion, and presented by such able men. Referring to photomicrographs Nos. 17 and 18, he was inclined to agree with Mr. Carlisle, as he could hardly see how a difference of only 5° C. would cause such a vast difference in the grain size. He was inclined to believe that the difference in structure was more a function of time and temperature than a function of the difference of only 5° C. Referring to the curve in Fig. 4, he did not believe as yet the fact had been brought out that, if several series of specimens were hardened at successively decreasing temperatures starting with 1300° C. by jumps of about 75° C., and each series was reheated in the manner indicated, the curves of each series would be somewhat lower, but more or less parallel to the original. Also the breakdown point would not occur at 600° C., but would occur at temperatures successively lower than 600° C. That to his mind was somewhat a measure of the poorer cutting efficiency of an underhardened tool. One speaker had asked for experience in upsetting bars into milling cutter sizes. At least a year and a half ago a large amount of that type of work had been in progress in America, and in milling cutters of 4 inches to 6 inches diameter, it was possible to obtain hardened fractures, perfectly refined and microscopically free from the deleterious segregations mentioned in the body of the paper.

CORRESPONDENCE

Mr. J. **Ferdinand Kayser** (Spartan Steel Co., Ltd., Research Department, Sheffield) wrote that the power consumed for the cutting tests was extremely great. He supposed that "Light" referred to the power required to drive the lathe before the tool commenced cutting, and the "Full Load" was power required when tool was cutting. Was that assumption correct?

He could confirm all the authors' remarks concerning the annealing of high-speed steels. As the authors had shown, slow cooling from about 900° C. gave a recalescence point at about 760° C. If the cooling were accelerated sufficiently that point could be depressed and the steel become harder the greater the cooling velocity. He (Mr. Kayser) had found that the final hardness depended only upon the rate of cooling through the temperature range corresponding to the recalescence point given with slow cooling (in that case about 760° C.), and that the rate of cooling through the actual recalescence point had no effect whatsoever upon the hardness. High chromium steels behaved very similarly to tungsten-chromium steels; for instance, an alloy of the following approximate analysis: carbon, 1·6 per cent.; chromium, 12 per cent.; and cobalt, 3·5 per cent., when cooled in air from 1000° C., gave a Brinell hardness of 601; when cooled in air to 650° C. and cooling then retarded so that time to fall from 650° C. to 265° C. was 1 hour 40 minutes, the Brinell number was still 601. Slow cooling that steel gave a recalescence point at about 740° C.

In the two cases just given the point was between 400° C. and 300° C., but with the retarded cooling between 650° C. and 265° C. it was much greater.

Dr. J. H. **Andrew** and Mr. G. W. **Green**, in replying, wrote that they were greatly indebted to Professor Howe for his remarks concerning the size of ingots. That dendritic configuration played a large part in the soundness of the finished tool had been made only too apparent from Professor Howe's own pioneer work, and that of Baeliew and Humfrey. The authors had had considerable experience with large ingots and all their data were in entire agreement with Professor Howe's remarks. The objection to larger ingots appeared to be proved not only by practice but also by theoretical considerations.

The suggestion by Professor Edwards that there might be an endothermic and an exothermic reaction occurring at one and the same time, which would accordingly vary the size of the critical point according to the relation in magnitude of the two changes, was interesting. Present knowledge of such complex steels as those under discussion was as yet insufficient to say definitely whether that interpretation would hold. That there was a definite increase in the magnitude of the 380° C. point with increase in initial temperature appeared to be beyond doubt. The authors had invariably found that to be the case almost regardless of the rate of cooling, while Yatsevitch in his paper commented particularly on that question. The low point was regarded by the authors as being distinct from the high point. More recent work of the authors' appeared to show that the upper point was due to the change from martensite to troostite, and the lower one to the transformation of austenite into martensite and its decomposition products troostite and sorbite. The increased magnitude of the lower point with rise in temperature was explained on the assumption that the transformation of martensite into austenite was more complete at higher temperatures, and naturally the greater the quantity of the austenite transformed, the greater would be the evolution of heat at the critical point.

Mr. Ashdown's suggestion that there should be a difference between the rolled and hammered tool was not borne out by practice. It should be remarked, however, that in dealing with steel used for tools the strength of the body of the tool was not so much under consideration as the efficiency of the cutting edge. So long as that part of the tool was austenitic it did not matter what the previous treatment of the tool had been, providing, of course, that it had sufficient strength to stand up to the job. Mr. Ashdown's suggestion as to up-ending billets in order to obtain cross as well as longitudinal forging was excellent, and might well be adopted with every hope of improvement; it would be especially applicable to large milling cutters.

With reference to Dr. Hatfield's suggestion that the brittle white constituent was tungstite of iron rather than a carbide, the authors wished to draw his attention to the microstructure they obtained from the decarburised piece of high speed steel referred to in their paper. Whereas in the partially oxidised zone the white constituent remained in relief and untouched, and indeed in every case was the last constituent to be oxidised, in the more or less completely decarburised area it was completely obliterated. Had that been tungstite of iron it would be difficult to see why the constituent would be attacked in that manner. The authors did not consider the evidence as conclusive, however, and quite agreed with Dr. Hatfield that it was as yet an open question.

Mr. Carlisle seemed so much concerned with the source of origin of the paper, namely, Manchester, that he appeared to have quite overlooked its actual contents. He stated that he did not know that high speed steel was cast at the same temperature that high speed steel was hardened at. The authors did not know that either. If Mr. Carlisle would refer to page 308, under the heading "Casting Data," he would notice that particular stress was laid on the facts that the temperature of the pots were only approximately correct, whilst those of the ladle were decidedly low. Mr. Carlisle suggested that the segregation found in electric steel was one-third the amount found in crucible steel; if so, judging from the analyses given by the authors of the high speed steel ingots, the segregation in the same class of steel made in the electric furnace must be one third of nil, a rather difficult figure to imagine. His remarks with regard to electric steel generally were, however, interesting. It was difficult to understand his differentiations between carbide segregation and chemical segregation.

While the authors were somewhat amused at Dr. Rogers' remarks, they warmly appreciated those of Mr. Howard J. Stagg, especially in regard to the up-ending during forging of high speed steel with the idea of eliminating the carbide segregation. The authors were in entire agreement with Mr. Stagg's suggestion that a difference of 5° in the hardening temperature would not cause such a vast difference in grain size as the difference in time. It appeared, however, that it was the rate of grain growth that increased so rapidly with temperature. The authors did not wish to infer that there was any particular size of grain relative to any one temperature, but that as the temperature was increased the increase in grain growth was greatly accelerated per degree rise in temperature as the high temperatures were approached.

The authors quite agreed with Mr. J. Ferdinand Kayser in his interpretation of the terms "light" and "full load," and were pleased to note that the remarks concerning the annealing of high speed steel were confirmed by him. The experiments quoted by Mr. Kayser with chrome cobalt steel were extremely interesting and served to confirm the authors' results. No doubt Mr. Kayser would agree with them in their statement that it was necessary completely to suppress the upper point, and, generally speaking, almost completely to suppress the lower point to obtain the maximum hardness.

SOME POINTS IN THE MANUFACTURE OF FILES.

By GEO. TAYLOR (Sheffield).

Steel.

At no time in the history of file-making has the importance of the file been realised so much as during the past four years, and probably at no time in its history has the need for reorganisation been so urgently required as now. During the time that scientific attention has been given to other branches of industry, the file trade has rusticated. By dint of stress from outside a few mild improvements have been made, but in the main things have gone along in a seemingly happy-go-lucky way, perhaps due in a measure to the idea more or less prevalent that file-making is not a very paying business. Keen competition and the lack of scientific investigation and organisation are the principal causes of this attitude.

Half a century ago nearly all files were made from crucible steel. To-day nearly all files are made from either Siemens or Bessemer steels. Exceptions are such files as warding, taper, and mill saw, and other very small files. In the Sheffield district, in point of chemical composition, the steels used fall between the following limits:

	Per Cent.		Per Cent.
Carbon	0·90	to	1·40
Silicon	0·10	,,	0·25
Manganese	0·30	,,	0·80
Sulphur	0·01	,,	0·05
Phosphorus	0·02	,,	0·06

On the Continent, and to a relatively less extent in this country, some files are made from milder steels of Bessemer origin. The amount of carbon may be as low as 0·35 per cent. Such material cannot be hardened in the ordinary form of lead bath, but must be handled by a modified form of hardening process in use in the tenth century, or earlier, which is more fully dealt with under "Hardening."

Of late years, with a desire to produce a better and more durable article, manufacturers have resorted to the practice of adding special elements to file steels, and fancy names, generally of a misleading character, have been given to files made from such materials. These special elements are chiefly chromium and tungsten. These elements are used in tool steels either to increase their effective hardness and the depth to which it penetrates, or to sustain a keen cutting edge for smooth finishing purposes. Neither of these objects are attainable by the present methods of file-making in anything like the sense in which they appeal to the maker of machined or ground tools. Whatever commercial advantage there may be in using these special elements in file steels, there is probably no great increase in the actual efficiency of the file, and there may be some decrease unless a number of oft-overlooked precautions are simultaneously taken. The hardness of the file tooth and the depth to which the hardness penetrates have never been grounds for complaint which can be remedied by adding chromium to steel, and the sharpness, efficiency, and durability of the teeth suffer less for want of tungsten than for want of care in controlling their size, shape, regularity, and the rake and clearance angles of their cutting edges.

From a large number of tests of both chrome and ordinary steel files made on the Herbert testing machine—files cut under the same conditions by the same man with the same angles on the chisel, and on blanks with the same Brinell number—the average results are about equal.

It is well known that files vary, and it is quite possible to obtain a file now and again which will show a very good curve when tested on the Herbert machine, but such results are largely due to accident or chance, and not to design, and arise owing to the unscientific way in which files are at present made. Many of the tests of chrome steel files have fallen much below those of ordinary files, showing that those extra precautions have been overlooked, which must be taken if chrome steels are to be worked to the best advantage.

No doubt in time we shall find good reason for adding special elements to file steel, or for leaving out some elements whose interference is only vaguely suspected. This part of the business lies very properly with the metallurgist, and when the same amount of care is given to this part of file-making as is already given to the making of other cutting tools, many of the problems which trouble the manufacturer will be removed, and he will be assisted materially in the production of a better article.

In relation to the manufacture of files, crucible and Siemens steels are to be distinguished chiefly by the different amounts of manganese which they contain. This element, more than the usual variation in the amount of carbon, determines the depth to which the hardness through and beyond the tooth of the file penetrates. It is objectionable in small files, chiefly because it causes them to harden intensively throughout, and makes them correspondingly brittle. It may be objectionable in large files too, both for that and other reasons. Siemens steels are also generally less free from roaks and other surface defects which, particularly in round files, might cause them to split on hardening. This, however, does not involve any serious amount of inconvenience and loss, as the roaks are mostly visible after grinding, and the blanks can then be rejected.

Soft files, due to the surface of the ingot and billets becoming decarburised in the reheating furnace prior to rolling, are not distinguishable until they are practically finished. For softness occurring in spots or patches, the rolling-mill is not necessarily to blame. It should be recognised, however, that most of the bars as they leave the mill or forge are surrounded by envelopes of carbonless metal, which may be increased in depth in the subsequent forging and annealing operations, and must be later entirely removed by grinding if soft files are to be avoided.

Fig. 1 is an enlarged photographic representation of a section of flat file steel showing the carbonless white envelope.

The troubles which afflict the file-maker, so far as the steel is concerned, might be considerably mitigated. He knows too seldom what the chemical composition of the material is which is delivered to him. (I have known the carbon to vary in presumably the same steel from 0·55 per cent. to 1·60 per cent.) Very often, too, he works up material for the sake of cheapness which has been found unsuitable for some other purpose.

The first thing, then, to be done is to determine what is the most suitable steel. Secondly, always to order to that analysis.

Thirdly, to insist on the cast number and analysis being given with each delivery of material. Fourthly, to check the analysis. Fifthly, from each delivery of material to examine the extent of decarburisation. In this way the examination will become a properly organised part of the file-maker's system and prevent many of the subsequent troubles he now experiences.

FORGING.

When M. Jars visited this country in 1765, he inspected the Sheffield and Newcastle file industries, and made some interesting notes on what he saw. Referring to Sheffield, he writes : "Specially noteworthy was a machine driven by water on which a single man made as many files in a day as fifty file-cutters could work up in the usual way." But the inventor and possessor of this machine, Thomas Lightowller, destroyed it out of caprice. This, I believe, had reference to a forging hammer. The first use of a water-driven hammer for file forging was made in Germany, and was called a Reckhammer.[1] However, practically all files were forged by hand; the smaller sorts, single hand; and the larger and heavier, double hand; *i.e.* by two men—a forger and a striker. The steam-hammer was first used in Sheffield for file forging about the year 1879. Hand-forging occupied a large number of workers for many years, and it was not until the introduction of the belt-driven hammer (Fig. 2) that hand-forging was superseded. Some files, principally very small sorts, are still hand-forged, but the vast bulk of the work is executed by belt-hammers and rolling machines. The rolling machines now in use (Fig. 3) are a great improvement on the earlier designs, and they have helped considerably to increase the output of files for all munition purposes during the war.

Breeze fires had been in general use for heating the blanks preparatory to forging, but with the advent of steam-hammers large coke fires were built. These continued in use after the belt-hammer was installed, until gas became recognised as the cleanest and most manageable means of heating. Many people still have their coke fires, and some of them believe that these possess a certain virtue not to be found in gas fires, in that decarburisation does not take place so readily. Fig. 4 shows the latest type of gas-fired furnace.

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[1] See Beck, "Geschichte des Eisens."

Decarburisation may occur no matter what kind of furnace is used, and is not necessarily more frequent as a result of the use of gas fires.

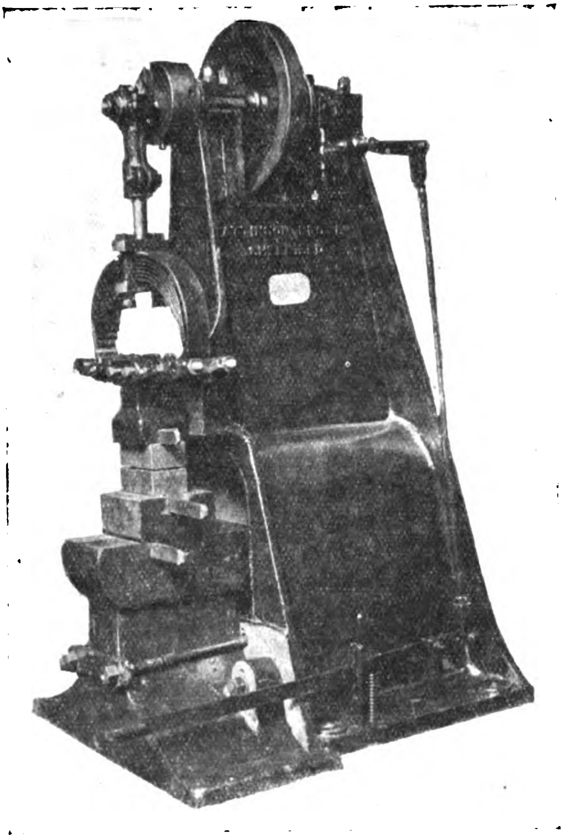

FIG. 2.—Belt-driven Hammer.

Whatever means are used to heat the file blank it is of the greatest importance that it should not be overheated. When a series of bars are being heated simultaneously, the forger should see that none of them become hotter than is necessary to give them the required shape before the temperature falls below dull redness. Nor should the bar which has to be drawn into a taper file have more of its length raised to a forging heat than will allow the taper to be practically formed. Steel which has been raised to a forging heat and not subsequently forged assumes a coarsely granular structure, which may or may not be remedied by subsequent annealing. If not remedied the hardened file is needlessly brittle in the overheated part, and may break in

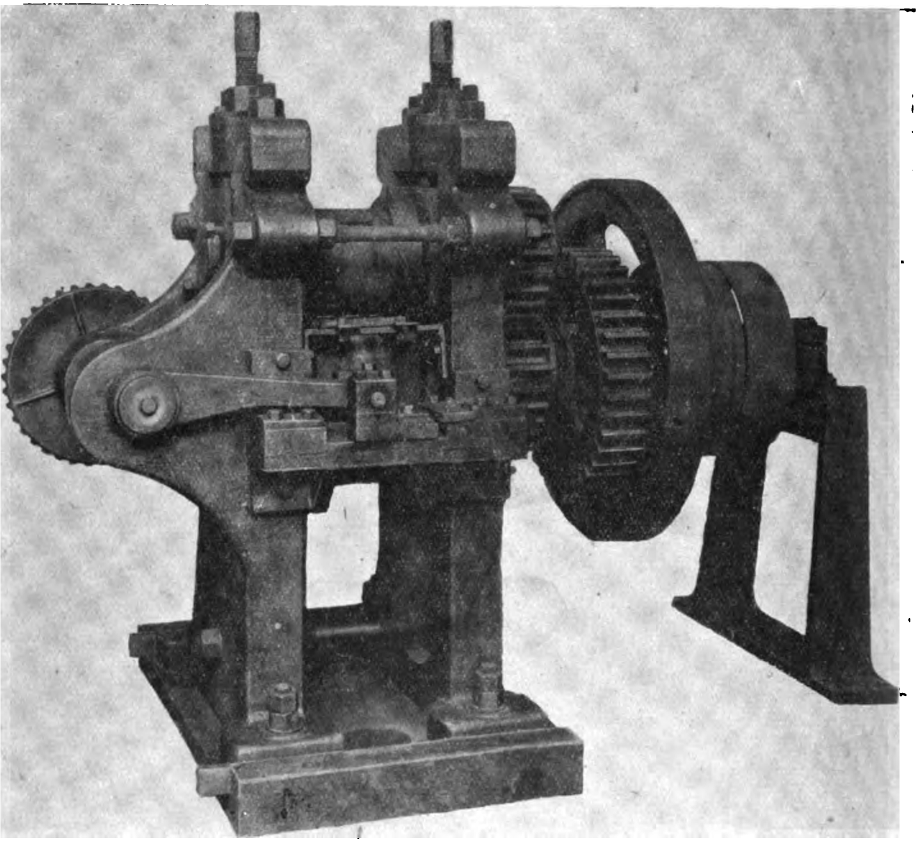

FIG. 3.—File Rolling-Machine.

straightening, cutting, or hardening, or it may break off short in use.

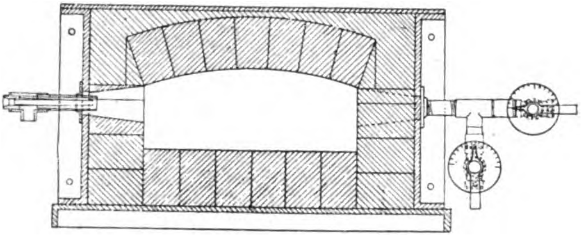

FIG. 4.—Gas and Air Blast Forging Furnace. Cross Section.

Fig. 9 is a section from a file which broke during the straightening after it had been annealed.

It is advisable that the forger should be instructed:

(1) As to the kind of material he is to forge.
(2) As to the temperature at which he must work.
(3) Not to leave heated blanks in the fire, but to finish them before leaving his hammer.

File forgers are rarely given such particulars; if they were instructed, not only would there be less overheating than now occurs, but they would develop more interest in their work.

If overheating is suspected it should be looked for just beyond the tapered portion. If the fractured surface in that portion is coarser than in the unforged part nearer the tang, the forger and not the rolling-mill is obviously to blame. Needless exposure of the file blank to high temperatures may increase the depth of the decarburised envelope, and lead to irregular patches of soft teeth towards the point of the file. The old saying that the "nature" has been burnt out of the steel, and it therefore will not harden properly, or has no longer the "body" necessary to give it the required strength, generally means only that the surface of the file is deficient in carbon, and the coarse crystalline structure allows a crack to be readily started and propagated through it. The demands made on the strength of a file at the tang end being comparatively small, some degree of overheating may be tolerated in that part, providing it is well-tempered after hardening; still, overheating of steel is always more costly than the proper kind of heating, though the difference may not always be readily perceived.

Another point of considerable importance in forging is the production of a uniform shape of blanks. Under present conditions it is practically impossible to produce quantities of blanks that are perfectly uniform, but as future developments in grinding and cutting operations will be based on uniformity of the forged blank, attention must now or later be given to this point. File-makers need the co-operation of engineers with a view to solving this and other problems in file-making, the urgency of which is apparent when we consider the higher organisation that exists in America and also in Germany, and the keenness of the competition with which we are likely to be met in the world's markets.

ANNEALING AND STRAIGHTENING.

The ancients had no need to anneal their file blanks preparatory to other operations. As they were made from iron, or very mild steel, all they had to do was to prepare a surface to receive the cutting. With the use of high-carbon steels arose the necessity of softening the blanks sufficiently to allow the metal to flow up into a ridge or tooth under the impact of the cutting chisel. The older furnaces used for this purpose were built of brick, and consisted of a fire-chamber in which the blanks were stacked. At the sides were holes through which the flames from the coal were drawn by means of a flue and damper. The smoky flames penetrated through the body of files and heated them to the proper temperature, as determined by the practised eye of the annealer. When the required heat was reached, the furnace damper was pushed in and the files allowed to soak, then the fire died down and was drawn. This operation was completed in three days. (See Fig. 5.) From this type of furnace a departure was made to a larger long type, with firing-chamber at one end, the lambent flames being drawn over the files, which were arranged in mild sheet steel trays, by means of a flue, the mouth of which was placed in the roof at the opposite end (Fig. 6). A variation on this type was that in which the flue was carried under the bed of the furnace.

The latest and most efficient type is the gas-fired furnace. Figs. 7 and 8 show two types of these furnaces in section to illustrate the working. By means of these furnaces it is possible to anneal much larger quantities of file blanks, and to do them quicker, cleaner, and with better control. All older types of furnaces are still in use, the idea being prevalent in some quarters that the smoky flames of the coal furnace are better for the files.

Pyrometric control of annealing temperatures is not universal in the file trade, but it is obvious that in the future pyrometry will be found as useful here as in other branches of the tool-making industry.

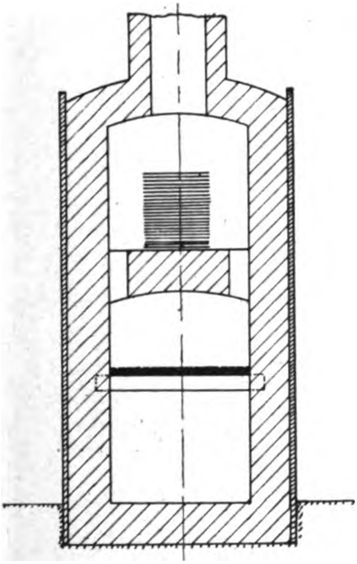

Fig. 5.—Annealing Furnace for Blanks (old form).

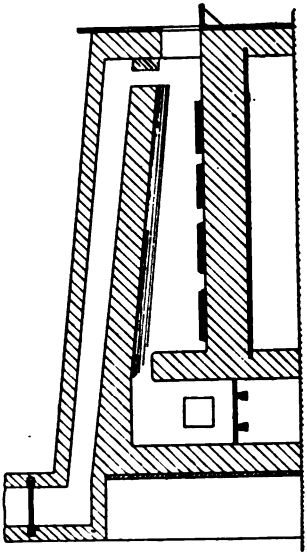

Fig. 6.—Annealing Furnace for Blanks (later form).

The main object of annealing the forged blanks is to make them soft, in order to facilitate the work of the grinder and cutter. Should the blanks be made as soft as possible? One would answer instinctively, "Yes, of course." And yet there are skilled men, file-makers for the last half-century, who maintain that 1 per cent. carbon steel, for example, can be made so soft that on cutting "the tooth will not rise properly." This statement is difficult to understand, but if one investigates the shape of tooth formed on copper, wrought iron, mild steel, &c., by the same chisels and machines as are being regularly used to cut ordinary file steel, it will be found that the same conditions as produce a reasonably good tooth on moderately softened 1 per cent. carbon file steel will not necessarily produce a desirable form of tooth on soft copper or wrought iron, or even on very mild steel. It may, however, be taken as a reliable fact

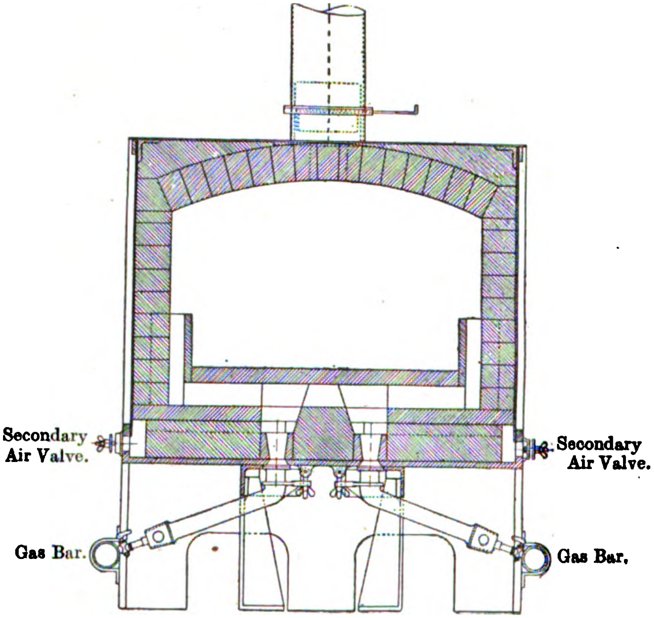

Fig. 7.—Natural Draught Gas Annealing Furnace.

that the softer the blanks, so long as the degree of softness is uniform and the shape of the chisel is suitably adapted, the better form of tooth it is possible to make, and obviously the easier and cheaper the grinding and cutting operations become.

In order to harden his chisels the file-cutter quenches them from a certain temperature between 750° C. and 800° in water. In the quenched state they are too brittle for use, so he reheats them to some temperature between 200° and 300°, and finds that they have become softer and tougher. If they are still too brittle he reheats them or tempers them to a still higher temperature until a suitable degree of softness and toughness has been reached. He knows that if the chisels had been quenched out in the first instance in warm water, oil, or molten lead, they would have been softer than they were after quenching in cold water,

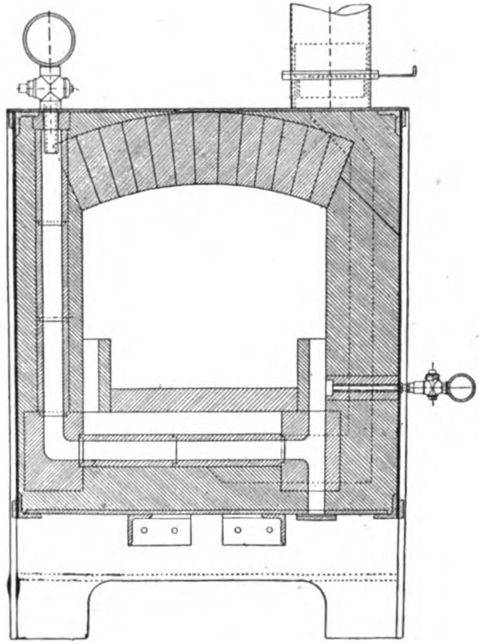

FIG. 8.—Low Pressure Gas and Air Annealing Furnace.

and he should therefore be prepared as a matter of experience to believe:

(1) That the hardness of steel depends on the rate at which it is cooled.

(2) That having once been hardened it can be softened to some extent by reheating or tempering at temperatures below or up to low redness.

It would be quite impracticable to cut efficient files from many forged blanks unless they were first softened. To make the softening operation absolutely imperative and give greater emphasis to the following observation, let us suppose that the blanks are as hard as possible; that is to say, let them have been water-quenched. If from this stage they are reheated respectively at 100°, 200°, 300°, 400° C., and so on, they become softer. At 500° C. a faint redness might be seen in the dark, and a hardened file blank after reheating to this temperature had a Brinell hardness number of 321. After reheating to 600° C. the Brinell number was 241; after 700° C. it was 187. In every case, during these observations, the file blank was kept at the stated temperature for two hours, and it was almost a matter of indifference, so far as its hardness was concerned, whether the file blank was allowed to cool in the air or quenched out in cold water. At a temperature of 700° C. we are on the verge of a sudden change, whose effect is clearly illustrated by the following table:

TABLE I.

Reheated to	Cooled in Air.	Quenched in Water.
700° C.	187	187
725° C.	170	187
750° C.	196	555
850° C.	241	555
950° C.	269	555

These observations show quite clearly that if it is intended to soften file blanks by reheating to a certain temperature and allowing them to cool in the air—a practice by no means unusual in the trade—then the nearer the maximum temperature reached approaches the temperature at which they would harden if water-quenched, the softer they become. If, however, this temperature is overstepped the blanks get harder, and this practice in endeavouring to attain the greatest possible softness is apt to be pushed too far and produce instead blanks of a mixed kind, some being much harder than others, which is always undesirable if regular work at fixed piecework rates has to be done. This method of "annealing" file blanks is therefore not commendable.

The only remaining alternative is to reheat the blanks to a temperature at which they would harden if water-quenched, and to make the subsequent cooling so slow that they remain suitably soft. The material referred to in the last paragraph, when cooled uniformly from 760° C. in twenty-four hours, had a Brinell hardness number of 156. It is not essential to keep the blanks in the furnace till they are stone cold; when they are no longer visibly red the cooling can, if desired, be completed with the doors and dampers up, or by drawing the files into the air. By this latter procedure the blanks can be made softer, and more uniformly soft than is possible by any form of reheating followed by cooling in the air. That the blanks are more apt to scale is true, but that can be easily avoided, and is in any case a comparatively small matter.

If the blanks have been overheated in the forge, the annealing furnace is the place to make that defect good; or at least to remedy the defect as far as it is remediable. The coarse crystalline structure due to overheating is not at all removed by the softening which depends on reheating and air cooling. The coarse may be replaceable by the fine structure only during the passage through at least that range of temperature which confers on the steel the capacity of hardening when water-quenched; and that range of temperature, as we have seen, can be used with effect only when the subsequent cooling takes place very slowly. These considerations will not appeal very strongly to those who never produce overheated blanks, but are set down here for the sake of completeness and the special benefit of the inquiring person who may at times be troubled with cracked files which seem to have gone wrong somehow.

The file-maker is very conservative in his views. He still continues to use steels containing so much carbon that the file is diffused throughout with a network of free cementite. This makes the file brittle and adds little or perhaps nothing to the usefulness or wearing quality of the tooth; it adds enormously, however, to the possibility of the teeth cracking during the hardening operation or breaking off in use. It frequently happens that the surface of the file, even below that portion ground away, becomes decarburised to a certain degree and so protects the file-maker against himself. Note, for example, that the free cementite in Fig. 11 stops short an appreciable distance below the surface of the blank.

But the serious objection to the use of the file steel containing over 1 per cent. carbon lies in the fact that such steel once overheated cannot be restored by heating to a temperature just above that from which it could be hardened. Fig. 9 may be taken to represent the microstructure of such a steel in the overheated state. When fractured the exposed surfaces glare and glisten. If the material is made into a file by the ordinary processes and hardened, a fractured surface has still a coarse, dry appearance, and such files break readily in use even if they happen to pass the ringing test. Such steel can only be restored to a finely crystalline state by heating it to a temperature at which the free cementite cell walls go into solution. When the steel contains as much as 1½ per cent. carbon, the temperature required will exceed 900° C. If exposed for a long time—say two or three hours—at that temperature, the outer portions of the bar which by partial decarburisation are lower in carbon, became seriously overheated, and one is faced with a fractured bar fairly fine in the mass, but surrounded by a coarsely crystalline envelope, which is sharply divided from the interior portions.

It is important that during annealing the file blanks should lose their shape as little as possible, not only because the subsequent straightening is unproductive labour, but because the blow of the hammer distorts and hardens the material in patches. Very severe blows may cause the parts struck to glaze in grinding or to damage the chisel in the cutting operation. These troubles are rarely ascribed to the straightening operation; less rarely, in fact, than they should be when one remembers that the straightener in some factories is instructed to leave the mark of the hammer face or edge in the blank, so that the grinder must perforce "bottom" the scale.

To wilfully make a more or less deep impression in the surface of the file blank in order to check the thoroughness of the grinding is but to replace one possible disadvantage by another. It is easy without the depression to see when the scale has been properly ground off. What the depression implies is that the grinder shall remove a measurable thickness of metal below the scaled surface in order that any carbonless surface envelope, as illustrated by Fig. 1, shall be removed. It is only on very rare and unavoidable occasions that the carbonless envelope would not be removed by the grinder without any precautions being taken. If, however, precautions are necessary, something less objectionable than the mark of the hammer face should be used.

If the surface of the blank is appreciably decarburised the entire surface of the impression left by the hammer is decarburised too, and if the impression is not "bottomed" on that part at least the cutting edges of the file teeth will be soft. A brief glance at Fig. 10, which represents on a magnified scale a section through a hammer mark, will make this matter clear. In Fig. 11 we have a photomicrograph taken through a dinted file blank after the carbonless envelope had been removed from every part save that which had been heavily struck by the straightening hammer. All soft spots in finished files are not due to the above causes, but many of them are directly due to the means taken to avoid them.

GRINDING.

Before grinding-stones were discovered, in the days when the first bronze and iron files were made, the surface which was to receive the "furrows" or "notches" to form cutting edges must have been prepared by means of a hammer. This would entail very skilful and laborious work. Perhaps after hammering they were rubbed with stones, which proceeding would lead to the making of grindstones to be turned by hand. This in turn, with the advent of the waterwheel and later the steam-engine, gave way to power-driven stones. Not until the middle of the last century did machine grinding begin to make its way, and now the bulk of grinding is done by machinery. The objects of grinding are to remove all scale and to give a flat, smooth surface to the file, so that the next operation of cutting can be executed properly.

If file blanks have hard patches, they have been "glazed" by the grinder; if they have soft places, he has not "bottomed" the scale. These are almost articles of faith in many factories. Indeed, these statements have been so firmly believed that grinders have actually been dismissed because they were held responsible for "soft files." In this respect the grinder has been most unfairly treated, and affords an instance, of which many might be quoted, of the lack of proper study and investigation of problems affecting the making of files, which has been, and still is, characteristic of file manufacturers.[1]

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[1] Since writing the above a "File Trade Technical Society" has been founded with the object, amongst others, of investigating such matters.

In the majority of cases soft spots, as we have seen, are due to the absurd precautions taken to avoid them. The forged blanks may be seriously decarburised below the bottom of the scale, but no one can tell whether they are or not except by making a microsection, and in any case the grinder is in no way to blame. A grinder has done his duty when he has delivered his work free from "blacks" and level on the surfaces. Either the rolling-mill or the forger is to blame—generally the former. If it is imperative that the grinder should remove a certain thickness of metal from each side of the blank, the most certain way to ensure this is to cut a mark to the required depth and insist on that mark being ground out. In some cases this has been done by means of a small pointed hammer similar to a pick. It is, however, not usually necessary to do more than remove the scale completely. If after this soft files occur, the remedy obviously does not lie in worrying the grinder.

The grinder is also not necessarily responsible for hard patches. For glazing pure and simple he is usually to blame, but in this respect the hand-grinder does not err. If the corner of a softened file blank be pressed heavily on to a revolving emery-wheel it can be quickly raised to incandescence. On being withdrawn the red-hot corner cools instantly, and will be found on trial to have hardened considerably. In this way, on a grinding machine the gritstone can be brought so fiercely on to the blanks that they are locally and momentarily made red-hot. The sudden cooling which follows causes the heated patches to harden, and lays up a store of trouble for the file-cutter. In a milder way, when a machine grinder is working with insufficient water and an excessive amount of pressure, the whole file blank may become hard. Not infrequently file-cutters complain that the grinder has "case-hardened" the blanks. This is a colloquialism to indicate glazing (the effect described). The softer the blanks, the less readily does the glazing occur; with blanks made from very mild steel its occurrence, for obvious reasons, is practically unknown.

There are four serious defects in grinding which exercise a deleterious influence in the cutting process. These are:

(1) The surface of the blank may be ground slightly concave.
(2) It may be ground slightly convex.

(3) There may be a wavy appearance giving a series of depressions.

(4) The surfaces may be covered with scratches due to a coarse gritstone.

If the first and second faults are not regarded as very serious, the cutter will endeavour, so far as "bastard" and rougher cuts are concerned, to meet the difficulty in the grinding of his chisel. But the remedy is not entirely successful, as the finished file does not possess a perfectly uniform surface. In the one case the file will not cut at the edges on the flat sides until the middle portion is worn down; in the other case the edges must be worn down before the teeth in the middle can come into operation. The only remedy with such files is re-grinding. This applies also to the third defect. The wavy appearance is due to the stone in the machine having worn very small and "dancing" on the file blanks. The same defect is seen, too, on files which have had the "over-cut" smoothed down by unequal pressure on an emery-wheel. In the finished file the defect can be plainly seen, and such files ought to be rejected as "wasters."

The fourth defect is a difficult one to deal with. It is caused not only in grinding, but in "stripping." The finish on a file blank is of importance, and it is the aim of the grinder to produce as smooth a surface as possible. Unfortunately, gritstones vary so much that, no matter how careful a grinder may be, he cannot avoid deep scratches on the blanks. Some stones are soft and fine-grained; others are hard and coarse, or to use a grinder's expression, they are "full of pebbles" and have no "muck" in them. These latter are responsible for the worst examples of scoring. When the hacker blades in the grinding machine are brought in contact with the face of the stone to level it, the coarse silica grains acquire sharp cutting points which dig into the blanks during the process of the operation and produce scratches. If such blanks are cut single without further work of smoothing, a series of serrations will be found on the edges of the teeth. These serrations can be well seen on the top edge in the magnified photograph of a single cut file in Fig. 12. If it is remembered that these serrations occur in material which has been brought by sudden distortion to a cutting edge, it is easy to realise not only that the cutting edge becomes thereby less effective and durable, but that they may, as they actually do, serve as starting-points for small hardening cracks which run transversely to the root of the tooth. It is customary, however, to strip practically all files that are to be single cut, and smooth double cut. This may be done either by means of a file or emery-wheel. This process, although it removes the grinding scratches, may replace them by others almost as objectionable. These remarks apply with even greater force to double cut files, except that the serrations are caused in filing the overcut as well as in the grinding operation. This is more fully dealt with under "Cutting."

In order to reduce the defects mentioned to a minimum, if they cannot be removed entirely, a different method of, and different materials for, grinding are required. Perfectly flat and smooth blanks, uniform in size, are required as a preliminary condition to perfection in cutting.

There is also another and very important reason why a new method of grinding should be invented—a human reason. This branch of the trade is unhealthier, dirtier, more laborious and more dangerous than any other, and those who work at it know they cannot look forward to a healthy vigorous old age.[1] The attention of engineers might be directed with useful and profitable results towards the invention of a grinding machine, or the adaptation of some existing grinder, in which an artificial wheel with a good supply of water could be used for the grinding of all files, large and small. The genius of the engineer has overcome much more difficult problems, and there is good reason to hope that this particular one will not long await solution once the requisite attention is bestowed upon it. Something has already been accomplished in this way for round files. The Stead process grinds round blanks automatically from the solid up to $\frac{1}{4}$ inch diameter. Those $\frac{5}{16}$ inch and above are first drawn taper under the hammer and then ground. The machine is a very greatly improved design on the gramophone needle grinding apparatus and produces uniform blanks perfectly round. The process is simple and very expeditious; of 4-inch round files as many as 8000 have been ground in three hours. The same arrangement may be developed to grind half-round files, with the certainty of producing files that have a perfectly rounded back.

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[1] The average life of a grinder is about forty years.

CUTTING.

In speaking of file-cutting, Theophilus (eleventh century) informs us that it was done by means of a double-edged cutting hammer, or a notching iron. The two-edged hammer was used up to the fifteenth century, when it gave place to the hammer and chisel. Early in the sixteenth century Leonardo da Vinci invented the first cutting machine. Following on this, in 1627, Mathurin Jousse invented another. Many other inventions followed, but with little success. Although machines had been used to some extent in France, it was not until about 1875 that they began to be used generally in Sheffield. Since their introduction hand-cutting has died down, and is at the present time a relatively unimportant industry. It is confined mostly to small files which might be distorted on the machine, and special shapes. Although there was formerly great controversy as to the respective merits of the hand and machine cut file, little interest is now taken in the subject.

The machine-cut tooth is more regularly formed, but does not vary in shape from the hand-cut tooth to any great extent. It was, and is, commonly supposed that the hand-cutter worked with a sharper chisel than the machine man, the former having what he called a " thin " and the latter a " thick " chisel. The " thin " chisel of the hand-cutter after being ground and whetted " long and short "—that is, with a long side and a short side—was supposed to give a forward rake to the tooth of the file. The opinion arose owing to the difference in the shape of the tools. In the important part of the tool, the cutting edge and angle, there is little or no difference. The hand-cutter's chisel may have a thin web, but it is the angle of his whetting that determines the rake of the tooth, and this angle is practically the same on the machine chisel as on the hand-cutter's tool (see Figs. 13 and 14). The hand-cutter's was found to vary along its length, so the angles were measured at three points. This question of angles is extremely interesting and important, because the rake of the tooth depends on the angle of whetting of the chisel in conjunction with the angle of inclination of the bed on which the file rests, or the machine head in those cases where the bed is horizontal.

The machine file-cutter grinds and whets his chisels for himself just as does the hand-cutter, and in just the same way. He endeavours to whet with equal angles for the overcut and with a "long" and a "short" side for the upcut. He does not know usually what the angles are that he makes, neither does he know the angle of inclination of the file bed or the machine head. His past experience and the way he has been taught are his guides. Consequently he may never whet the same angle twice, and this accounts to some extent, particularly if he is careless or hurried, for the differences which are to be seen in the rake of file teeth.

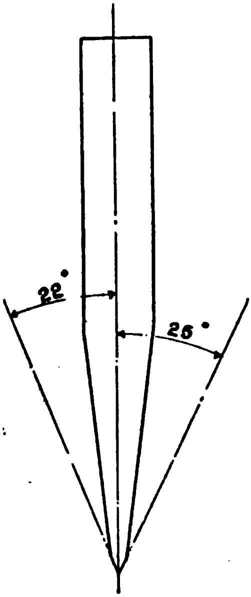

FIG. 13.—Machine-Cutter's Chisel.

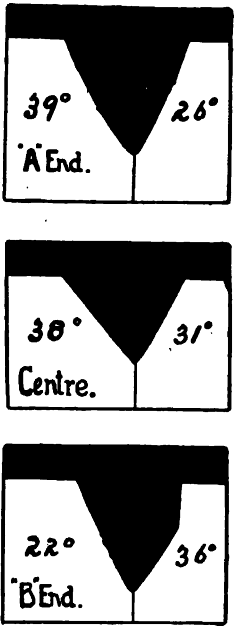

FIG. 14.—Hand-Cutter's Chisel. This chisel was found to be unevenly whetted, and so the angles were measured at each end and in the centre.

All commercial files, with the exception of certain milled varieties, have teeth which slope more or less backward. Fig. 15 may be taken as a fair sample of the teeth to be found on such files, the arrow indicating the direction in which the file is intended to move. Let us suppose now that the file-cutter who is working on bastard cut files endeavours to whet his chisel with equal angles, and to include an angle of 60°. If such a chisel operated in a machine whose bed slopes at an angle of 15° to the horizontal, it is clear that the tooth formed must have a rake of minus 15°, because $15° - \frac{60°}{2} = -15°$. (See Fig. 16.) The observed average rake of a large number of commercial files of English, American, and continental origin was found to be minus 8°. This form of cutting edge is certainly very strong, and the tendency is to vary its obtuseness according as the blanks are more or less soft. The greatest negative rake we have measured was 24°, and the greatest positive rake 7°.

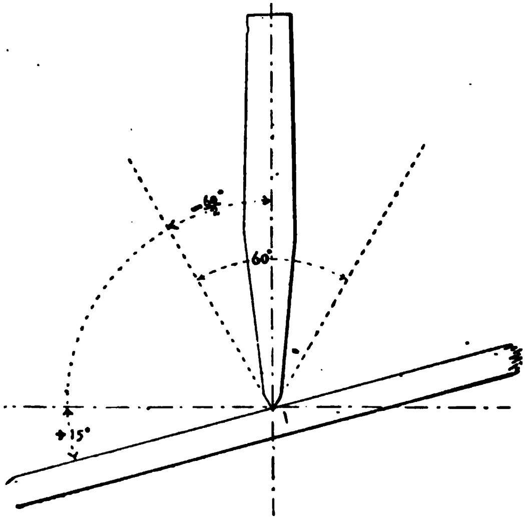

Fig. 16.—Angle of Rake.

When first the question of the rake of file teeth began to be investigated there were many protestations that the rake was positive and not negative. The absurdity of making files with backward sloping cutting edges was quite fully realised—nevertheless, when the files were examined, the teeth were found to have a negative rake.

A tool with a negative rake may scrape, if it is sharp, but it cannot cut. The finger may be drawn with impunity across the edge of a razor if it is sloped backwards, but not if it is sloped to the slightest extent forward. The teeth of a file may be looked upon as a gang of small cutters, and like the teeth of the milling cutter, they should be formed with a positive rake. The amount of rake would naturally be determined according to the kind of work a file is put to. For broad surface filing it would be best to use a file with a greater positive rake than would be necessary on narrow surface work. Fig. 17 represents the kind of filings removed by a file cut with a negative rake, and Fig. 18 those cut by a file having a positive rake. In every other respect the two files were as nearly alike as they could be made. That the former, as we have said, scrapes rather than cuts, is borne out by a comparison of the two photographs.

It is a most difficult matter, even on a single cut file, to determine by the unaided eye whether the rake of the teeth is positive or negative. It can, of course, be easily calculated when the angles of the chisel and the machine bed or head are known; when neither these data nor any form of instrument are available, a most useful indication is the relative amount of resistance offered to the thumb and first finger as they are drawn on opposite sides along the file from point to tang. The value of this test is largely a matter of experience, and even then may be deceptive. The most accurate method of measuring the rake is to make a section and take an enlarged photograph, but this involves the destruction of the file. Fairly satisfactory results can be obtained, however, by the use of the instrument illustrated in Fig. 19, if the following directions are observed: Blacken a portion of the file over a candle flame. Place the base A of the instrument over the blackened portion so that it stands at right angles to the upcut. Take the fine needle E and make a bright mark along the bottom and close up to the face of the teeth; the use of the lens enables this to be done with considerable accuracy and uniformity. Whilst the mark is being made and the tube B is tilted forward, the face of the tooth can be seen. Now rotate the tube slowly backward until the line at the base of the teeth just disappears from sight. This happens when an imaginary line passing through the small eye aperture, C, and the centre of the lens, D, lies along the face of the tooth. A pointer attached to the tube and moving over the protractor scale gives the inclination of this imaginary line to the vertical, and indicates to what extent the rake of the tooth is plus or minus. The question of the rake has been dealt with out of its rational order, because it is the most important item the manufacturer has to settle in relation to the shape of the file teeth.

The next point to be considered is the overcut. The object of the overcut is to provide a number of furrows which will divide the subsequent upcut into a convenient number of separate teeth, and we can imagine that the shape and also the size of the furrows might be allowed to vary considerably without impairing the efficiency of the teeth. I am not aware that this point has been investigated experimentally. From certain experiments I have made, although uncompleted, I am convinced that variation from the present standard will lead to the production of files whose cutting efficiency is considerably higher than that obtaining at the present time. The number of teeth per inch in the overcut as compared with the upcut must be considered very carefully, as it certainly has an important bearing on the efficiency of files.

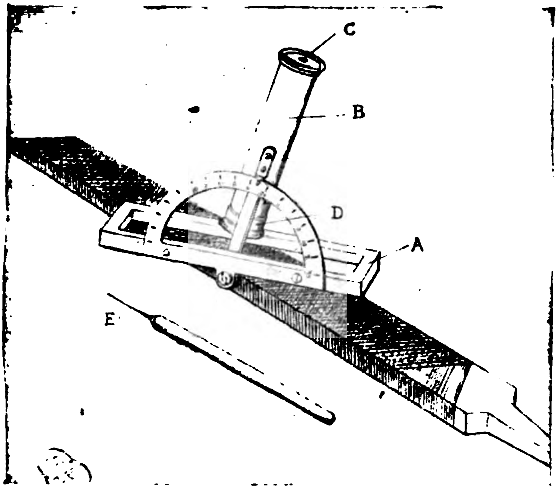

FIG 19.—Instrument for Measuring Rake.

The shape of file teeth as viewed from the face is determined by the overcut. Now it is customary to smooth down the ridges raised during the process of overcutting, either by filing them or by the use of an emery-wheel. This is a process where the greatest care and attention is needed, because its influence is second in importance only to the rake. Unfortunately, this is one of the points most often overlooked, and very, very carelessly dealt with. It is the source of almost infinite variation in the shape of file teeth, and no attempt has been made, so far as I know, to standardise the operation.

If the ridges are made too flat the metal does not rise into a proper tooth when the file is upcut, and when the teeth of such files are photographed one sees clearly (Fig. 20) that such teeth may be strong, but they are not sharp, and the file will need to be pushed by a strong man if it is to be used on broad surface work. On the other hand, if the upcut is filed insufficiently, the tooth formed by the upcut will flow into a sharp point, as illustrated in Fig. 21. This form of tooth is much too delicate for general use, and although it may cut well on broad, flat surfaces like lathe beds, for example, where the pressure exerted by the man per tooth is necessarily small, there is always a tendency for the teeth to strip or break off. For use on narrow surfaces it would be of little value, because all the teeth would break. This particular file when tested with the Herbert machine, on the standard Herbert bar, cut faster than any file we have seen, but did not last long.

When the overcut is filed down, no matter whether it be by means of a file or emery-wheel, the ridges should be left with smooth tops. The scoring action of both file and emery-wheel is detrimental to the finished file, in so far as a tendency is given for the teeth to develop cracks. These cracks weaken the teeth, and they readily break off in use. Fig. 22 shows a file with scoring marks left in the ridges of the overcut, and Fig. 23 shows the resulting cracks in the teeth. Great variation exists in this respect between files made by different firms, and there is no remarkable uniformity in files made by the same firm. I do not presume to state to what extent the overcut should be filed. That would depend more or less on the varying degrees of hardness in the file blanks and the force of the blow exerted, and the overcut would have to be filed accordingly.

As already stated, the upcut serves to make the metal flow up into the final tooth shape. If the overcut has been filed irregularly, there will be teeth which vary in shape and also in efficiency. They will be flatter or more rounded, according to the degree of filing on parts of the file. On some files which have had the overcut flattened by hand over an emery-wheel, variation of the pressure exerted by the man has resulted in a wavy appearance similar to that produced sometimes in grinding. The resulting file has then sharp and less sharp teeth, or if the filing has been excessive, blunt and more blunt teeth, and the filing efficiency of such files may thereby be reduced 50 per cent.

If a file has blunt teeth it is an extravagant waste of both energy and time, and no matter how little has been paid for it, it is likely to be a dear article. The shape and rake of file teeth should, without doubt, differ according to the kind of work upon which they are to be used, just as turning and planing tools are made with differently shaped noses; but in every case where it is intended that a file should be used as a cutting tool the teeth should have a positive rake. To do this the cutting angle of the chisel must be whetted to such a degree that, taken in conjunction with the angle of bed or machine head, a forward tooth will result. By way of example we will suppose that the machine bed is sloping at an angle of 15° (see Fig. 16), and we desire to produce a positive rake of 5°. It is obvious, therefore, that we must whet the chisel to form a cutting angle of 10° on that side which raises the face of the tooth: $15° - 10° = 5°$. This is one of the most important problems in file manufacture, and no satisfactory solution can be obtained until machines are installed in factories for whetting chisels to any desired angle. Fig. 24 shows angles of machine chisels, two of which were taken at random. No. 1 was for upcutting second cut files; No. 2 for overcutting bastard cuts; and No. 3 for producing a positive rake on bastard cuts. No. 3 was ground and whetted on a special machine for the purpose.

The force of the blow exerted by the cutting machine should be sufficient to strike right to the bottom of the overcut. If this is not done the tooth formed (see Fig. 23) is weaker than it need be, and breaks off more easily at the root. It is easy with a good hand lens to see whether this has been properly done, and at the same time the shape given to the cutting face of the tooth can be observed. The lens which forms part of the instrument

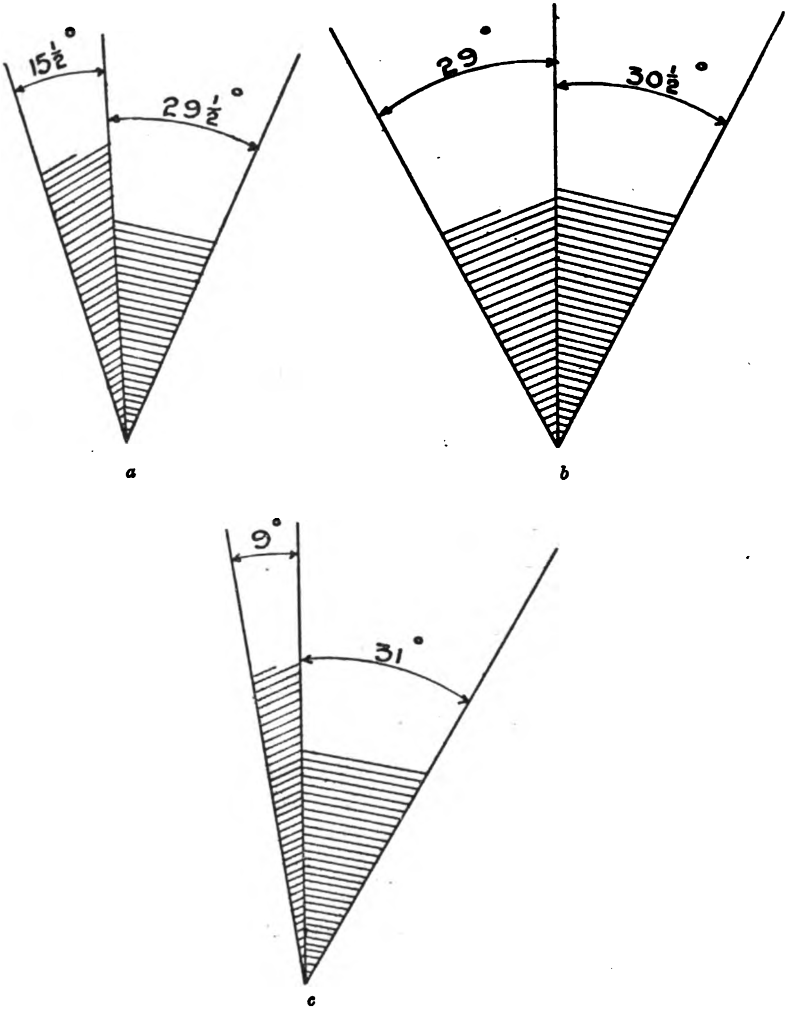

Fig. 24.—Angles of Machine Chisels.

shown in Fig. 19 is detachable, and is especially suitable for the above purpose, as it brings a large field evenly into focus.

There remain now to be considered the three important questions of (1) angle of clearance; (2) inclination of the angles of overcut and upcut to the axis of the file; and (3) the number of teeth per inch. With regard to the clearance angle, I am in complete agreement with Mr. Edward G. Herbert, and cannot do better than quote his remarks on this point in conjunction with the diagrams in his paper on "The Testing of Files and Tool Steel." Mr. Herbert says:

"The slope of the back face of the tooth, or clearance, is very difficult to measure, because it is not a plane surface (see Fig. 25). It is probably very important in relation to the durability and to the total output of work. A file which has worn out has the ends of its teeth flattened or rounded. When the area of contact of the teeth with the work attains a certain value, great pressure is required to cause the teeth to penetrate the metal. The amount of work that can be got from a file therefore depends largely on the volume of tooth available for wear before this limiting area is attained. Fig. 25 shows two file teeth with different clearance angles. The part of the tooth available for wear is shaded, and it is evident that the tooth with greater clearance presents a much greater volume of tooth for wear before the limiting or slipping area is presented to the work. There is a limit to the amount of clearance that can be safely given, because the tooth must not be left so weak as to break under working conditions. . . .

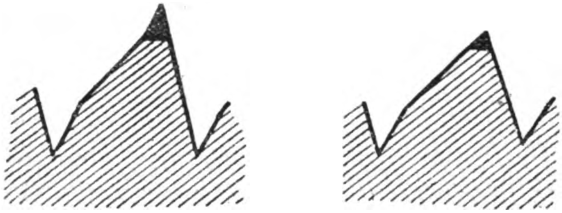

FIG. 25.—File Teeth with different Clearance Angles.

"Examination of the files shows that these angles are extremely variable, *and it is certain that uniformly satisfactory results cannot be obtained unless correct angles are ascertained and maintained by means which will leave no scope for variation of judgment on the part of the workman.*"

(The italics are mine, and such significance is contained in the passage, that all file-makers ought to give their most earnest attention to it.)

The inclination of the overcut and upcut to the axis of the file has considerable influence on the efficiency of the tool, and in this respect the variations that exist, not only amongst files of different makes, but also amongst files by the same maker, are very great. The angles found on the files of one maker were as follows:

TABLE II.

	Hand Smooth 12.	Hand Bastard 12.	Hand Smooth 14.	Hand Second Cut 16.	HalfRound Bastard 14 (Flat Side only).	Square Bastard 14.	Cotter Bastard 12.
Overcut .	55°	58°	53°	59°	57°	54°	55° to axis
Upcut .	73°	73°	67°	70°	74°	70°	75° „ „

These files were taken at random from a new batch, and illustrate the lack of uniformity which is to be found in almost any batch of commercial files.

It may be said that the inclination of the overcut fixes the position of the teeth in relation to each other, and that of the upcut fixes the angle at which the face of the tooth is presented to the work. The possible variation in the inclination of the overcut and the upcut to the axis of the file can be advantageously manipulated to produce files to cut particular kinds of metal. This is done in the case of files intended for use on brass and aluminium. Some results of varying the inclination of the upcut of files are to be seen in Figs. 17 and 18. If the upcut lies obliquely across the file, the filings will be similar to those shown in Fig. 18. If, however, the file tooth lies squarely across the file, then the filings have the shape of a volute spring, as shown in Fig. 26. But in either case, if the tooth has a large negative rake, the filings may be shapeless scrapings, like those in Fig. 17.

The number of teeth per inch, and the ratio between "overcut" and "upcut," are also factors in the efficiency of the file. Variations of both factors within fairly large limits may be made without the efficiency of the file suffering. With the upcut nineteen teeth per inch on a 14-inch bastard cut file, variations in the overcut from six to fifteen teeth per inch may be made without loss of cutting efficiency. Sufficient experiments, however, have not been made in the ratio variations to enable any standard to be accepted as the most satisfactory. Mr. Herbert is right when he says: "The ratio may prove to be one of the most important factors in file efficiency."

It is not intended to discuss the question of file-testing, but reference must be made to a point which always crops up whenever files are put under test; that is, the variation in the two sides of a file. Mr. Herbert says: "It has been suggested that the side first cut is injured during the cutting of the second side by contact with the block on which it rests. File-makers generally favour the explanation that the difference is due to a variation in the sharpness of the cutting chisel. It is said that a chisel will only cut five sides before it needs whetting. Perhaps it does not always get whetted as soon as it needs. If, therefore, a batch of files are all cut on one side, then turned over and cut on the second side, it must often happen that one side of a given file is cut with a newly whetted chisel and the other with a chisel that has become blunt."

The difference in the efficiency of the two sides of a file may arise, and does arise, from a combination of causes. These may be enumerated as follows: (1) Unequal blow of the chisel; (2) unequal filing of the overcut; (3) unequal whetting of chisel; (4) working too long with chisel; (5) the effect of the file bed; and (6) the variation in grinding; that is, the more or less complete removal of the decarburised envelope. Furthermore, the cutting edges of a file may not always lie in the same plane along the 6 inches of its length tested. There is no need to labour these points. They are to be expected more or less as greater or less care is exercised, but it is extremely doubtful that the two sides of a file chosen at random can be uniform under the present system of manufacture.

The extreme top of the teeth are sometimes bent backward, and very rarely may be accidentally bent forward even. All machine cutting, at any rate in this country, is executed from point to tang. After cutting a tooth the chisel is withdrawn from the impression made, and the traverse of the machine bed brings the blank forward to receive the next blow. If the chisel has not quite cleared the tooth before the bed moves forward, it catches on the tooth and bends the extreme tip of it backwards. Many of the newer forms of file-cutting machines are continuously fed forward by a screw instead of the older form of ratchet motion. When the machine bed is being fed forward continuously, the chisel must always be withdrawn against the face of the newly formed tooth, and the pressure between the two is the force with which the bed is being fed forward. On hard steels the tooth may resist this pressure without being bent backwards, but on soft steels the tips of the teeth would be very apt to become pushed backward without being able to spring again into normal shape. An occurrence of this kind increases the disadvantage of a negative rake which already exists, and may make a tooth hopelessly inefficient in spite of the main face having a positive rake. Only a small portion of the tooth of a file is worn away in actual use. The rake of this portion only determines its cutting efficiency, and unintentionally, in the way suggested, this may be made better or worse. Generally it becomes worse; the instances in which it is actually made better are very rare indeed, and amongst those rare instances it is by way of being a miracle that one should be chosen haphazard for testing purposes.

The following particulars refer to two files taken from the same batch. They were cut by the same man on the same machine with the same tools, and both were intended to have a rake of minus 5°. The efficiency of the two sides of the same file were fairly concordant, that is, both sides of file A did badly, and both sides of file B did well, when tested on the Herbert machine and bar. The curves produced by one side only are reproduced in Fig. 27. It was only after the tested files had been sectioned and photographed that their curious behaviour was explained. These photographs are reproduced in Fig. 28 and speak for themselves. The cutting edge of A has had the original negative rake increased, and that of B has been transformed into a tool with a very efficient positive rake.

The obvious means of avoiding the undesirable form of tooth in file A is to cut the teeth progressively from tang to point, on the same principle as adopted in the earliest of file-cutting machines by Leonardo da Vinci and Mathurin Jousse. By doing this the chisel will not pass up the face of the tooth and cause the tip to bend backwards. The best means of regularly producing teeth like those of file B remains a matter for investigation.

HARDENING.

Many formulæ have been given during past centuries for preparations to be used in the hardening of files. That referred to under the heading of "Steel" as being in use in the tenth century is described by Theophilus Presbyter. It was in reality a sprinkling powder and was used for large files. The powder was prepared from ox horn by charring and pulverising together with salt. When the file was "white hot" this powder was sprinkled profusely all over it, and again heated in the charcoal fire blown by bellows. As soon as the powder had accomplished its work the file was quenched uniformly in water and then dried. "In this way," says Theophilus, "you will harden everything

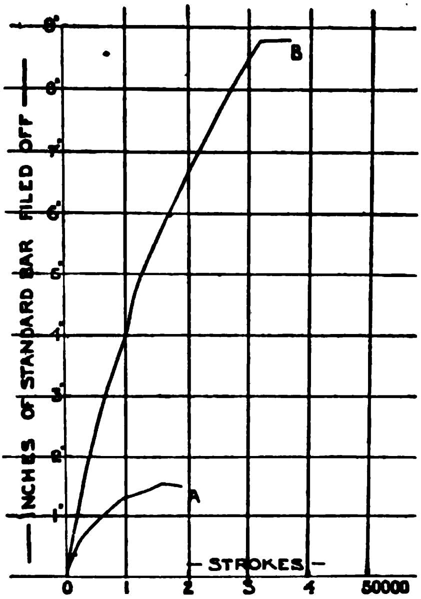

FIG. 27.

made of steel." In Sheffield, in the eighteenth century, files were hardened in a somewhat similar fashion. The files were smeared with ale grounds and then covered with powdered hoof and sea salt. After drying they were heated in a coke fire and then quenched. Ale grounds have been in use for a very long time; fine sharps, bran and flour, also have been used as covering to protect the teeth, especially of fine cut files, as they were pushed backwards and forwards in the breeze fires.

In modern practice there are two methods of heating files for hardening: one by means of breeze fires, which we may call the old way; and the newer way by means of the lead bath. The lead may be heated by cokes or by gas. When first lead began to be used there was great difference of opinion as to the respective merits of the two methods. It was contended by those who used the hearth that the use of lead was responsible for a large proportion of soft files. This contention is still held to-day by some people. The main support of the argument seems to rest on the fact that in some cases where files have been soft after lead hardening, they have been quite hard when re-hardened from the hearth, and this has been accepted as conclusive evidence that superiority lay with the hearth.

It does not seem very conclusive, however, when from repeated experience we know that such files as have been soft the first time hardening from lead, have been quite hard on a second and proper heating in the lead. If a file has been heated to the requisite temperature, and is not hard after quenching, the fault lies, not with the hardener, but must be sought in other directions, as we have indicated earlier. Such mixed lots of steel are used in the making of files, that it is very difficult for the hardener to work uniformly. Furthermore, he is working all day quenching in water the temperature of which is constantly rising. I have known the temperature rise so much that it was quite impossible to hold the hand in it. Again, if a workman is careless or "on the push" to get through a large amount of work, the probability is that some of the files will be quenched below hardening heat. These conditions may operate in both methods, and will explain how soft files may arise from hardening.

There can be little doubt that uniformity of heating is obtained more easily in the lead bath than in the hearth. Besides, being

PLATE XVIII.

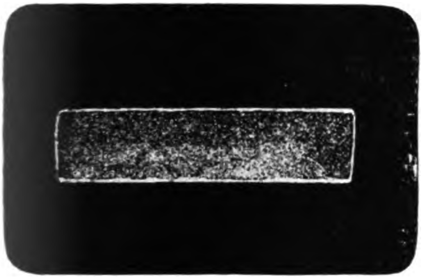

Fig. 1.—Section showing carbonless envelope.

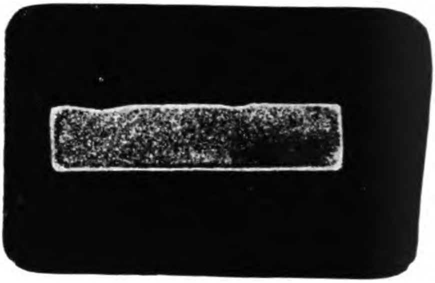

Fig. 10.—Section through hammer mark.

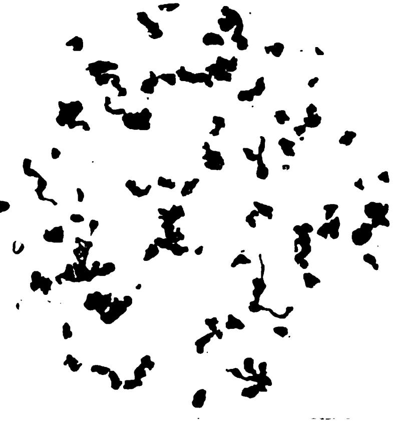

Fig. 17.—Filings (negative rake).

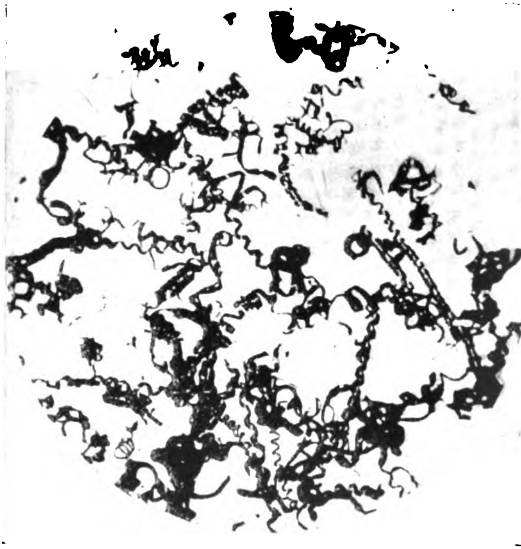

Fig. 18.—Filings (positive rake).

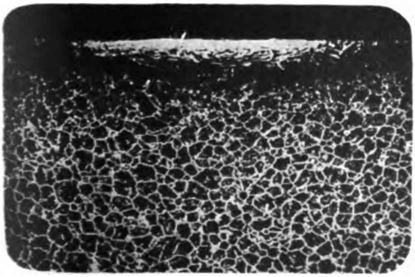

Fig. 11.—Demarcation of free cementite.

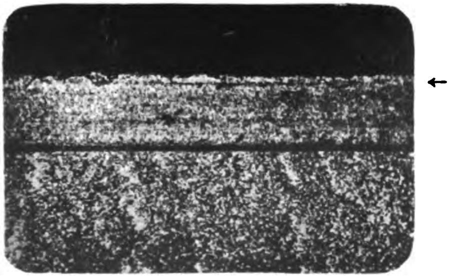

Fig. 12.—Showing serrations on edge of teeth.

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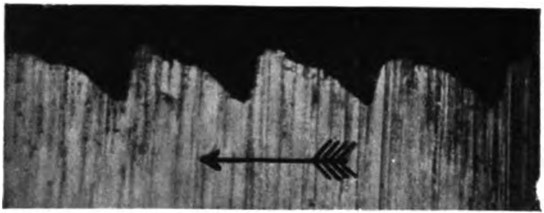

Fig. 15.—Teeth sloping backwards. File teeth with negative rake.

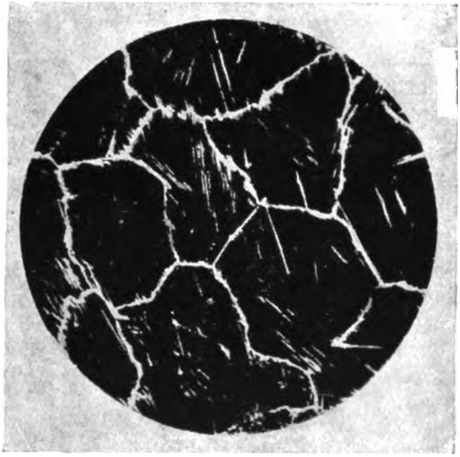

Fig. 9—Microstructure of overheated steel.

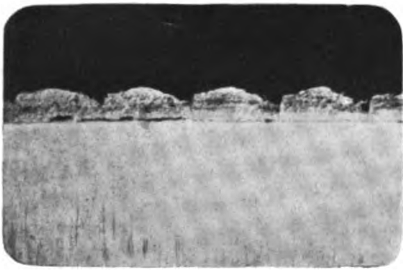

Fig. 20.—Teeth on ridges made too flat.

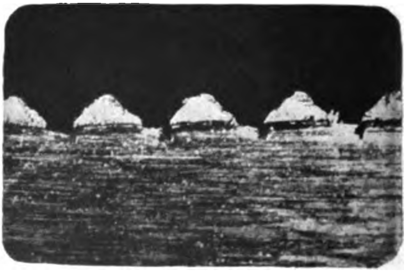

Fig. 21.—Weak pointed teeth. Overcut insufficiently filed.

PLATE XX.

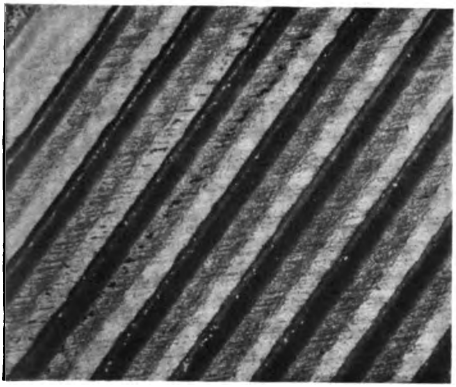

Fig. 22.—Scoring marks in ridges of overcut.

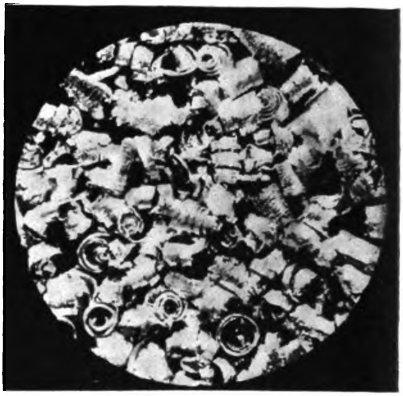

Fig. 26.—Volute-shaped filings.

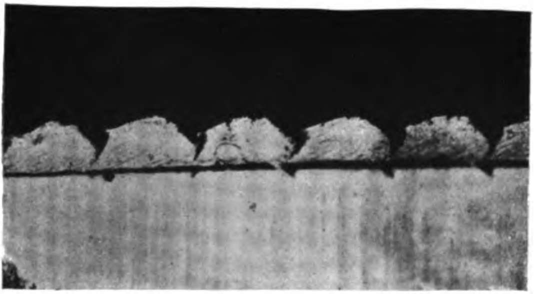

Fig. 23.—Cracks in teeth.

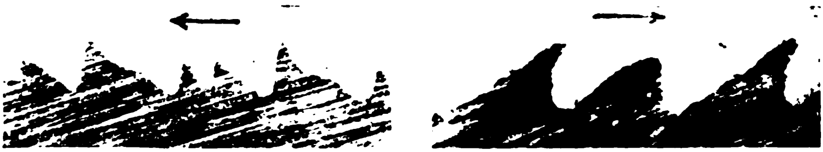

Fig. 28.

a—Increased negative rake.

b—Positive rake.

cleaner, the lead bath is more manageable. Fig. 29 shows the latest type of gas-fired lead bath in section to illustrate the internal arrangements. To get the best results it is advisable to use pyrometers either of the "Sentinel" or "Indicator" type. The uniformity of the temperature of the bath can be maintained very well by the use of sentinels if they are used in the following manner:

If it is desired to work at a heat between 750° C. and 780° C., procure two pieces of ordinary iron gas-piping with one closed end. The length should be about 10 inches, or as long as desired for the bath. Stamp on each tube the melting point of the sentinels to be used. In the first case this will be 750° C., and in the second 780° C. Take two pieces of wire longer than the tubes and bend one end in the form of a hook. After placing the sentinels in their respective tubes, raise to melting point and insert the wires. On cooling the salts will solidify and fasten the wires so that the tubes may be lifted by them. The tubes are now placed in the lead bath and the temperature raised sufficiently to melt the 750° C. sentinels, but not those in the second tube, whose melting point is 780° C. This can be easily

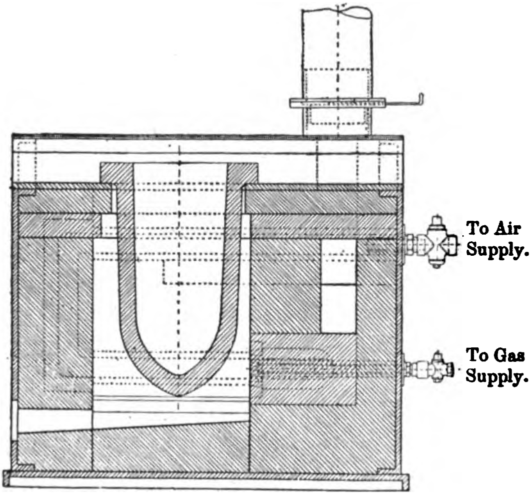

Fig. 29.—Low Pressure Gas and Air Lead Bath Furnace. Cross Section.

ascertained by lifting the wire. In this way it is comparatively easy to maintain the heat desired, and to test the temperature of the bath in any part. A regular use of the sentinels or the indicator will considerably lessen the risks of quenching at a lower heat than is necessary to properly harden the files.

In conclusion, I plead for a definite and organised system of working in the manufacture of files—a system which will ensure a reliable quality of steel always obtainable, and the production of blanks of uniform size and quality.

Scientific investigation throughout the whole of the processes is urgently needed, and makers ought to establish research rooms in their factories for that purpose. If it is considered undesirable that this should be done in each factory, then I would suggest that the Manufacturers' Association should agree to establish a central research laboratory well fitted with every convenience for conducting experiments; under the charge of a well-qualified manager. The results obtained would then be available for all manufacturers, and we could reasonably look forward to a great improvement in the efficiency of the file and the methods of production. This would mean that the English file trade would receive a great stimulus—a thing we desire and hope to see.

I am indebted to Mr. Harry Brearley for the use of his experimental notes on the subject, and also for suggestions made in revising the paper. I should also like to draw attention here to the valuable and highly interesting memoir by Mr. Frémont[1] on "The File," to which members interested in the subject would do well to refer. My thanks are also due to Messrs. Richmond of Warrington, who have kindly supplied me with drawings of gas-heated furnaces.

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[1] "Études éxperimentales de Technologie Industrielle," par Ch. Frémont, Numero 49, *La Lime*, Paris, 1916.

DISCUSSION.

Professor H. M. **Howe**, Honorary Vice-President, said he did not think it was possible to consider too strongly the recommendation of the author that the conditions of making files should be studied systematically by a competent research body. That was in line with the movement of the times, and it would appear to one who was very ignorant of the subject of file-making that it was particularly a matter which would require very careful and diligent research, that the extreme hardness could be best obtained without excessive brittleness only through very careful manipulation of the temperature, and that with the very high carbon steels, which were so extremely sensitive, to proceed without actually measuring the temperature was hardly consistent with the present condition of steel metallurgy in other respects. He hoped that the author's plea that a systematic research might be established would be carried out. Everyone was very greatly obliged to him for putting before them so clearly a matter which was of very considerable scientific interest and also of very great practical interest. The file was such an invaluable instrument, and so many files gave out very much too early, that everyone welcomed any information with regard to making files more excellent.

Dr. T. **Baker** (Rotherham) said that at the time he received the paper he had the question of some defective files under investigation. He had found most of the peculiarities or defects mentioned in the paper in the particular samples he was considering, and there was no doubt at all that the files had been made from strip which had been rolled at much too high a temperature. The files themselves all broke in the ringing test, with a very coarse crystalline fracture, which microscopic examination showed to have been caused by a very well-developed cementite network. That network could not have been produced in the hardening process, except under very abnormal conditions, and must have occurred at some earlier period. He had occasion to go into the works, and from what he could see there it was quite clear that there was room for considerable improvement in manufacture. The paper gave a considerable amount of information to the file-maker, and had come at a very opportune moment when, as far as he had been able to ascertain from the study of defective files, there was considerable room for improvement and for the adoption of more scientific methods in the manufacture of files.

Dr. F. **Rogers** (Sheffield) said he did not think any paper could more strongly emphasise the importance of research in what might be called a very commonplace branch of industry. No industrial operations were really commonplace; they were all worthy of investigation and then of systematisation upon technically the best possible lines. To the great mass of the public a file was only a rough piece of steel that made a nasty noise which set ladies' teeth "on edge"; but it was a great deal more than that. The author had submitted nearly every phase of file-making to scrutiny, both the mechanical and metallurgical considerations. Several of those aspects demanded a full discussion, but he (Dr. Rogers) would confine himself to one particular point, and his remarks would apply, with modifications as to temperatures, &c., to the discussion of Messrs. Andrew and Green's paper on high-speed steel. Referring to a diagram which was the same as that given on p. 386 of Messrs. Hanson and Hurst's paper on case-hardening, he said that file steel was generally to the right of the point S, and it was important to remember the rapid rise of the line SE with increase of carbon. There were two main factors to consider in choosing an annealing process; one was the softening of the 0·9 per cent. carbon steel (that was, the eutectoid portion); the other was the possibility of taking cementite into solution upon hardening. On pp. 356–357 Mr. Taylor referred definitely to the particular type of annealing—namely, at a temperature just over the critical temperature (say 730° C.). That method applied excepting when there was a coarse development of cementite. Mr. Taylor very happily brought out a point which he (Dr. Rogers) had emphasised to a number of people in Sheffield trades, namely, that it was not essential to cool the steel slowly right down to cold, nor anywhere near it. It was quite sufficient to cool down very substantially below the 690° point. Lack of appreciation of that point had caused enormous loss of possible output of furnaces. Furnaces generally cooled very much less rapidly as the temperature fell, so that the useless period of slow cooling was often twice as long as the useful period, and in the case of a small furnace that often might mean only one batch per working day when three could have been obtained, by throwing the blanks out or even merely opening the furnace, when the temperature had fallen to the point indicated.

Dr. J. E. **Stead**, F.R.S., Vice-President, said he noticed a reference in the paper to the "Stead process." It was not his process, but he was very pleased to be associated with a gentleman of the same name who had made a speciality of the investigation of files. During the time when the discussion was very active with regard to martensite, pearlite, troostite, and other "-ites," he happened to grind a file down until all the teeth were eliminated and the face was parallel and smooth. He then etched it in acid. The roots of the teeth were troostite and between the roots martensite, a very remarkable illustration of martensite and troostite side by side. In annealing there was a range in which there was a most rapid divorce of the pearlite. On heating from a high temperature and slowly cooling to a low, the softening effect mainly occurred in passing through that particular range, just below the critical points Ar1, 2, and 3. Professor Howe had devoted a great deal of attention to that work. Many years ago one Sheffield firm made a point of determining what was the difference by annealing at a high temperature and cooling down very slowly, and simply heating for a short time at about 700° C. It was found that half an hour's annealing at just below the critical point produced the same amount of softening as was produced by the long heating and slow cooling from 800° C. There was one advantage, however, in heating above the critical point, and that was that if there did happen to be a rather coarse structure in the steel it was broken up and became fine, and the steel was improved. The Institute was under a great obligation to the author for the valuable and exhaustive paper he had read.

Mr. G. TAYLOR, in reply, thanked the members for their kind remarks. So far as the ordinary processes of industrial manufacture were concerned, he thought the question of file-making ranked high amongst those which ought to receive attention. It had suffered a great amount of neglect in past years, and, for that reason, ought to receive a proportionately greater amount of consideration now.

Extremely little had been written about files, and most of what had been written was by foreigners. It was, therefore, high time that British people seriously took the matter in hand, along with certain other manufacturers, and made a real attempt to standardise their productions so that they would again occupy the place they would never have lost had that attention been given which ought to have been given. There had been a book written by Mr. William Turner in 1862 on the manufacture of files, but he had not been able to get a copy. In Dr. Beck's monumental work, "Die Geschichte des Eisens," there was a large amount of information about files. He would commend the remarks of Dr. Rogers to the notice of the members. It was a most difficult thing indeed in Sheffield to convince file manufacturers on the point of leaving the files in the annealing furnace until they were stone cold. If the advice given in the paper were followed in regard to that particular point alone, manufacturers would increase their output tremendously, and be better able to supply the large demands at present made. He realised that the paper was very limited in scope. Although he had endeavoured to cover a good deal of ground, there was a large amount of material that he would have liked to put in, but could not do so on account of considerations of space. He hoped in the future to be able to produce in one volume all he could find in reference to file-making.

IMPROVEMENTS IN THE CASE-HARDENING PROCESS.

BY D. HANSON, M.SC. (NATIONAL PHYSICAL LABORATORY, TEDDINGTON), AND J. E. HURST (ACTON).

THE present paper has been written as the result of an investigation into the prevention of flaking and chipping of the case in certain case-hardened articles during and after grinding. The articles in which the greatest amount of trouble was experienced were gear wheels of various kinds, used mainly in automobile and aero-engines and made from a case-hardening nickel steel containing 2 to 3 per cent. of nickel, but these were by no means the only articles in which failures of this kind were experienced, and the same defects were found in cam-shafts and other articles made from a straight carbon case-hardening steel. The articles were all made, so far as the metallurgical treatment is concerned, according to what was, and still is, widely considered to be good case-hardening practice, and were subject to pyrometric control at all stages during the carburising and hardening treatments. The results obtained were, however, such as to make the authors realise that considerable improvement was desirable.

Some of the causes of this type of failure are well-known. They include :

(*a*) Excessive concentration of free cementite in the case, particularly when this excess is arranged in the form of a coarse network surrounding areas in the steel which existed as large austenite grains at the end of the carbonising operation.

(*b*) An excessive amount of non-metallic enclosure in the steel.

(*c*) " Segregation " of the ferrite of the core on the one hand, and of the cementite of the case on the other, with the production of sharp differences in composition in adjacent portions of the steel.

(*d*) Local tempering of the steel during grinding.

Of these (*a*) and (*c*) appeared to be the most probable causes.

A consideration of the process by which the articles were made led to the conclusion that the conditions, especially in the case of the nickel steel, were such as might readily lead to the formation of fairly considerable quantities of free cementite, and an examination of some of the fractured gears showed that, even after the outer portion (about 0·01 inch thick) had been removed, an appreciable network of cementite was left. A few experiments were sufficient to show that the removal of this network overcame practically all the difficulty, and that other causes contributed but little to the failure. The methods by which this may be avoided, together with the theoretical reasons on which they are based, form the subject of this paper. Among other things, the authors have devised certain modifications of the case-hardening process, which have been used with great success, and which they think could find fairly general useful application.

PART I.

THEORETICAL.

Theory of Case-hardening.

The theory of case-hardening has been discussed by a large number of workers, both in the Journal of the Institute and elsewhere, but an account of some of the principles underlying the process is necessary in order that the reasons for the modifications in practice which have been introduced may be more readily developed.

The object of case-hardening is to produce on the surface of the case-hardened article a layer of steel having a higher carbon content than that of the original article, so that, after submitting the article to a suitable hardening process, it shall possess a "skin" of extreme hardness, while the centre portion remains relatively soft. The usual method of attaining this object is to heat the article in contact with a suitable carbonising reagent or "cement," under which conditions carbon combines with the iron and gradually diffuses into the mass of the steel.

It is well established that iron in the α (or β) condition has practically no solubility for carbide of iron (Fe_3C), and case-hardening, as it is ordinarily understood, cannot therefore take place at any temperature at which the iron is in this condition. The process only becomes possible at a temperature at which the transformation to the γ state has commenced. Now, in case-hardening carbon steel, which is in general mild steel containing about 0·1 per cent. of carbon, the change to the γ state commences immediately the point Ac1 (about 720° C.) has been reached (Fig. 1), but at this temperature only a small portion of the total iron of the steel has become transformed, *i.e.* that which, with the cementite of the steel, normally forms the constituent pearlite. At the temperature of this transformation point, however, the transformed pearlite, now austenite, which, it must be remembered, forms but a small portion of the steel, is saturated [1] with carbide, and consequently this austenite exhibits no tendency to dissolve more. Not only is it saturated with respect to carbide, but it is also saturated with respect to ferrite, or α-iron, and at this temperature the austenite remains unaltered in the presence of excess of either ferrite or cementite. In other words, the austenite which exists in the steel at this temperature is of eutectoid composition. If, now, the temperature be raised above this point, the equilibrium conditions become altered, and the austenite becomes able to dissolve a larger amount of either ferrite or cementite, whichever is available. This is clearly represented by the ordinary equilibrium diagram of the iron-carbon alloys (Fig. 1). The composition of the transformed pearlite at the transformation temperature is represented by the point S at the lowest corner of the austenite field, and at this point austenite can have only one fixed composition. At higher temperatures the lines GOS and SE represent the solubility of ferrite and cementite respectively in austenite, and the points at which these lines are cut by any particular abscissa indicate the limits of composition of the austenite which can exist at that temperature. If austenite be heated slowly above 720° C. in contact with excess of ferrite, its composition at any temperature is indicated by the point at which the temperature abscissa cuts the line GOS, while, if excess of cementite be supplied, similar changes of composition with temperature are indicated by the line SE.

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[1] The term "saturated" is applied here, and throughout this paper, to the constituent "austenite" of the steel, and in this connection it has the meaning which is usually associated with it in physico-chemical literature. It refers to a solution, solid or liquid, in constitutional equilibrium, in which the solvent contains in solution the maximum amount of solute which it will hold; this maximum concentration is a function of temperature, and the term "saturated" should therefore always be referred not only to the solvent and solute, but also to a particular temperature. This is the true scientific meaning of the term "saturated," and it is used only in this sense in this paper. The expression "saturated steel" has been applied by some metallurgists to a steel of eutectoid composition. In the authors' opinion this use of the term is quite unscientific. A steel of this composition can only be called "saturated" when it consists of austenite at the eutectoid temperature. At high temperatures austenite will dissolve additional amounts of either ferrite or cementite, so that at temperatures above the transformation point austenite of eutectoid composition is unsaturated. Such a steel would be better described as "a steel of eutectoid composition," or perhaps "eutectoid steel."

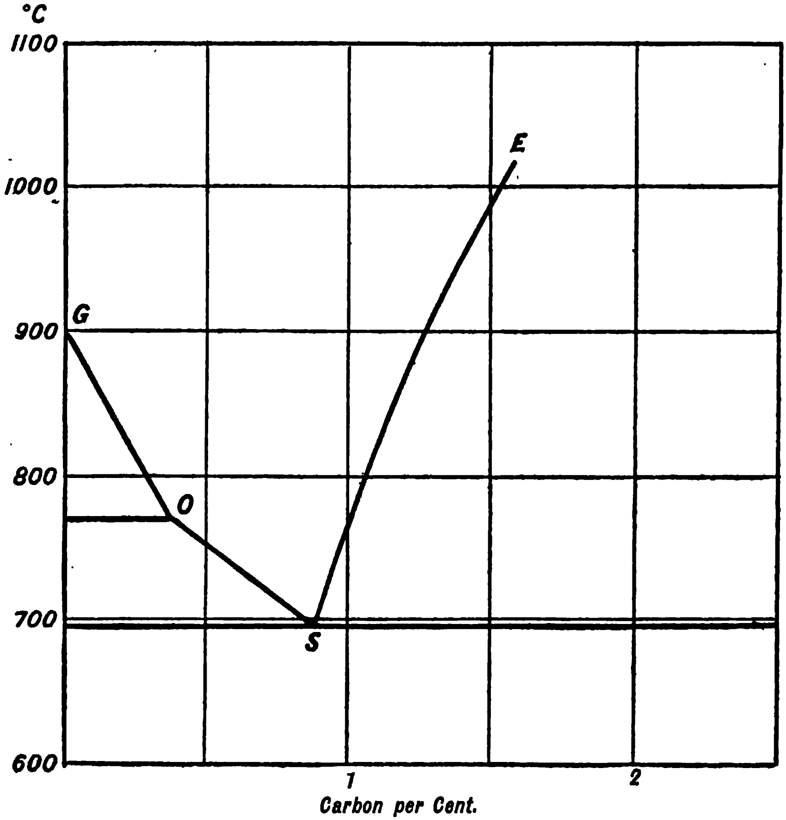

FIG. 1.

If a mild steel be heated to a temperature slightly in excess of the eutectoid temperature, the transformed eutectoid dissolves some of the ferrite in the steel, which simultaneously becomes transformed into γ-iron. The austenite areas therefore become slightly increased in size, and their carbon content becomes slightly decreased, but at the same time they become unsaturated at that temperature with respect to carbide. If, now, this heating be carried out in a carburising mixture, those portions of austenite which are on the surface of the steel are also able to dissolve carbon from this mixture, and therefore become unsaturated with respect to ferrite, a deficiency which is supplied by the untransformed ferrite in the steel. Carburisation can therefore proceed by the simultaneous absorption of carbon on the one hand, from the carburising mixture, and of iron from untransformed ferrite on the other. This process is obviously very slow, for it can only take place through areas which form but a small proportion of the total mass of the steel. As, however, the temperature increases, the quantity of austenite increases, with a corresponding increase in the velocity of carburisation until a point is reached—depending on the carbon content of the steel, and generally about 900° C. for most case-hardening carbon steels —when the whole mass consists of austenite. Commercial case-hardening, in which the time factor is important, is practically always carried out above the critical point, A3, of the steel.

Solubility of Carbide in the Case.

It has been pointed out that the solubility of carbide in austenite is represented by the line SE. At the point S the maximum concentration of carbon which the steel will hold in solid solution is that of the eutectoid, but as the temperature increases so does the maximum carbon concentration increase. From the diagram in Fig. 1 we see that, in simple iron-carbon alloys, at the eutectoid temperature 0·9 per cent. of carbon can be held in solution; at 800° C. 1 per cent. can dissolve; at 900° C. 1·2 per cent. can dissolve, while at 1000° C. 1·5 per cent. represents the limit of solubility. Thus it is evident that, not only does the velocity of carburisation increase with rise in temperature, but so also does the maximum carbon content which it is possible to obtain in the austenite of the case.[1] At the usual commercial case-hardening temperature, 900° C., the normal carbon content of austenite in contact with excess cementite is 1·2 per cent.

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[1] The authors also wish to state most emphatically that they do not deny the theoretical possibility of producing free cementite by carburising under favourable experimental conditions at any temperature at which Fe_3C is a stable phase, either above or below the critical range. It is known that iron can be converted entirely into Fe_3C by suitable carburising above or below the critical range, but the conditions under which this is possible are not those which are met with in ordinary case-hardening practice.

The actual carbon content of the austenite at any point in the carburised case depends on:

(*a*) The maximum carbon concentration which can be held in solution at the carburising temperature.

(*b*) The rate at which the carbon is absorbed at the surface.

(*c*) The rate at which it diffuses into the non-carburised core.

(*d*) The time during which the operation is continued.

For any particular steel (*a*) and (*c*) are both functions of the temperature, while (*b*) is dependent both on the temperature and the cement, *i.e.* on the nature and velocity of the reaction as a result of which the carbon enters the steel. The process of solid diffusion is slow, and most of the commercial cements are vigorous in their action, so that at the usual case-hardening temperatures carbon tends to pass into the steel at a greater rate than it can be removed by diffusion into the interior, with the result that the austenite of the outer layers of the steel soon becomes saturated with carbide, after which the rate of absorption at the surface is largely governed by the rate at which diffusion can take place into the interior of the steel. Other cements, however, such as some of the gaseous mixtures recommended by Giolitti, are less rapid in their action, and by their means cases of very considerable thickness can be produced in which saturation of the austenitic outer layers of the steel with carbide at the case-hardening temperature is never reached. The explanation is, in all probability, that the rate at which the carbon passes into the steel by diffusion is sufficient to bring about the removal of the carbon from the outer layers before they become saturated with carbide.

It is evident, therefore, that if the cement be of such a nature that it tends to impart carbon to the steel at the case-hardening temperature at a rapid rate compared with that at which the carbon tends to be removed by diffusion, then the outer austenitic layers must become saturated at that temperature with respect to carbon. Many of the commercial cements are of this type, and it is therefore clear that, under normal working, using one of the common cements, the concentration of carbon in the outer layers may approach very closely the saturation point of the austenite of the steel at the case-hardening temperature.

Formation of Cementite Network.

The formation of a network of cementite, of the kind indicated in the early part of this paper, requires that certain conditions be fulfilled. The cementite which forms this network is that which normally separates above the eutectoid point, and the network can only be formed in hyper-eutectoid steels. Further, the condition in which the cementite exists depends on the rate at which the steel cools over the range Ar3–Ar1. If the steel be cooled rapidly, as by quenching, and in some cases by air cooling, separation cannot take place, and the whole mass remains in a martensitic condition. If the rate of cooling be somewhat less rapid, partial separation of the cementite may occur, and it comes out in interlacing needles which, though undesirable, are less harmful than a continuous network. If the rate be extremely slow as, for example, if the steel be allowed to cool down normally with a very large furnace, the cementite is deposited slowly from solution in the form of large isolated crystals and exists as such in the cool product. There is, however, a wide range between these limits, in which the cementite separates in the characteristic form of a continuous network, and the usual practice of withdrawing the boxes from the furnace and allowing them to cool in air is quite favourable to the production of such a network.

It is seen, then, that the practice which is commonly adopted of carburising with a fairly vigorous cement, at a temperature considerably in excess of the eutectoid temperature followed by cooling in the box, is that which favours the production of a network of cementite in the outer portion of the case.

Hardening of the Carburised Product.

The prolonged heating in the carburising box, to which the case-hardened articles are subjected, has a harmful effect on both core and case which, for the highest grade of work, necessitates a subsequent careful heat treatment in order that this effect may be removed and the article brought into its best possible condition. For this purpose a double quenching is adopted. The articles are first heated to a temperature slightly in excess of the upper critical point, Ac3, of the steel, followed by quenching in a suitable medium, whereby the core is refined, and this temperature is followed by a final rehardening from a temperature slightly above the Ac1 critical point, with the object of refining the case and bringing it into its best possible hardened condition. The reasons for this treatment are well understood, and are described in most text-books. The effect of such treatment on any cementite network which may exist in the case may now be considered. If the amount of excess cementite over the eutectoid composition is less than is required to saturate the austenite of the steel at the temperature of the upper critical point of the core, then it is clear that on heating to that temperature for a reasonable time this cementite will dissolve and will not be redeposited on quenching. If, however, the cementite is more than is required for saturation of the austenite case, then reheating to this temperature will not result in its complete solution, and free cementite will remain in the quenched article. In any article in which the austenite of the case has become saturated with carbide during the carburising operation, and in which the network has been allowed to form, the complete removal of this network can only be attained if the article be quenched from a temperature at least as high as that at which carburisation took place. The subsequent heating to the lower temperature for hardening will have no effect on the network, for the temperature is not high enough to cause any appreciable solution of the excess carbide. This treatment will, in fact, lead to the precipitation of any dissolved excess, but this excess is deposited in the form of rounded particles, which are practically without effect on the mechanical properties of the case and have little or no embrittling action, while the effect on the wearing properties is likely to be beneficial rather than otherwise.

Consideration of Reactions in Relation to Carbon and Nickel Steels.

The above considerations may now be discussed in relation to the usual practice in case-hardening (*a*) carbon steels, and (*b*) nickel steels:

(*a*) *Carbon Steels.*—The usual practice in case-hardening carbon steels is to heat the articles in contact with a cement for a sufficiently long period to obtain the necessary depth of case, at a temperature which is seldom less than 900° C., and is sometimes in excess of this. The articles are generally allowed to cool in the box, and the subsequent refining and hardening operations are carried out at about 900° C. and 760° C. respectively. Under these conditions the formation of an appreciable network should only occur in the finished product if the temperature of carburising is much in excess of 900° C., and in modern works, in which pyrometric control is established, this temperature is not often exceeded by an appreciable amount. The refining treatment which is applied to the core is here suitable for refining the coarse network of cementite in the case, and trouble should only be experienced where the carburising temperature is much in excess of that indicated, or where the refining treatment is not correctly carried out.

(*b*) *Nickel Steels.*—The nickel steels call for rather more detailed consideration. In the first place, their critical points are lowered by the presence of nickel, the effect on A3 being greater, in general, than on A1. In a 3 per cent. nickel steel containing 0·1 per cent. carbon, for example, the Ac3 point is at about 800° C.—about 100° C. lower than in the corresponding carbon steel—so that nickel steels may be carburised at temperatures considerably lower than carbon steels. The addition of nickel not only lowers the critical points, but it also lowers the velocity of penetration, so that, in order to get the same depth of case in the same time, a higher temperature is required. Practical considerations of this kind have led to a fairly wide adoption of a temperature of about 900° C. for case-hardening nickel steels —a decision which has, in many cases, probably been influenced by the fact that carbon steels give satisfactory results when the same temperature is used. The result of using a carburising temperature greatly in excess of the eutectoid temperature is to favour the production of a carbon concentration in the outer parts of the case greatly in excess of the eutectoid concentration, with the consequent production of a pronounced network of free cementite on subsequent slow cooling.

The refining treatment which is given to nickel steels differs in some respects from that given to carbon steels. The refining temperature of the core, which is about 800° C., is lower than that for carbon steels, and, what is more important, much lower than the usual carburising temperature. Furthermore, in the case of these steels, in which the critical range is short, and in which a slight overheating of the case above the Ac1 point is not harmful, a single treatment at a temperature of about 800° C. is generally considered sufficient to refine both case and core and, after quenching, to give a material of satisfactory properties throughout.

It will be seen, therefore, that in this process, in which a high carburising temperature is very liable to produce a high carbide concentration which is not refined by the subsequent heat treatment, a cementite network, with its accompanying defects, may be readily produced.

Methods by which the Cementite Network may be avoided.

Methods which suggest themselves for preventing the formation of an excess of cementite in the harmful form of a network may be (*a*) methods by which the excess cementite, once it is formed, is distributed by suitable treatment in a less harmful manner, and (*b*) methods of case-hardening in which the process is so arranged that a serious excess of free cementite is never formed.

The methods which come under classification (*a*) may consist of:

1. The prevention of the separation of the cementite as a network in the steel at any time by quenching the articles direct from the carburising box. Slow cooling over the critical range is essential to the formation of a network, and if the material be quenched in the first place from the case-hardening temperature this separation can never occur, while the subsequent treatments to which the articles are submitted are such that the method of distribution of the carbide does not become harmful. In many cases this method is difficult to apply in practice, especially where a number of intricate parts must be treated in the same box. The method of tipping the whole contents of the box into water is hardly practicable where freedom from distortion is necessary, while in the case of nickel steels, which should be quenched in oil, the difficulties are still further increased. The method of quenching from the boxes is practicable and useful in a number of cases, but it must be remembered that it can in

no way replace the refining treatments, and must be considered as a preparatory operation only.

2. Reheating the article, after cooling, to such a temperature, probably the carburising temperature, that all the cementite becomes redissolved, followed by quenching. This process is in some ways better than the previous method, in that it is under better control, but it involves an additional treatment in a process which is already lengthy, and is likely to find little favour on that account. It also offers undesirable opportunity for surface oxidation of the case and increases the amount of distortion.

These methods are identical in principle. They ensure the retention of the excess carbide in solution in the austenite, from which it is only precipitated during subsequent operations in a harmless " globular " form.

Methods which come under the heading (*b*), and which may be described as preventive measures, include:

1. *The Use of a Less Vigorous Cement.*—If the reaction between cement and steel be slow, then the normal rate of diffusion may remove the carbide into the steel at a sufficiently rapid rate to prevent the eutectoid composition being reached on the surface before the required thickness of case is obtained. The use of a gaseous cement, or the method of " isolating " the cement from the articles to be carburised, as suggested by Giolitti, would appear to be applicable, and the authors believe that these methods have been used with success.

2. *By the Regulation of the Temperature during Carburisation in such a Manner that Excessive Carbide Concentration is not obtained.*—This method seemed to the authors to offer many advantages, if only it were possible to apply it without increasing the practical difficulties or unduly prolonging the operation. In this effort they have, they think, been entirely successful, and an account of the experimental and practical results which they have obtained is given in Part II. of this paper.

It is evident that a case of approximately eutectoid composition may be obtained by carburising with a fairly vigorous cement at a temperature only slightly in excess of the eutectoid point, but it is equally evident that such a method is far too slow to be practicable on a large scale. The method which has been adopted does, however, possess practically all the advantages of the slow method indicated above, without being markedly slower than the methods ordinarily in use. It consists in but a slight modification of existing methods. The box containing the articles is placed in the furnace, and the carburising operation is carried out, as in existing practice, for a period sufficiently long to obtain a depth of case somewhat less than is desired in the finished article, and the authors have found that one-half to two-thirds of the final depth is in most cases satisfactory. The temperature of this operation is usually about 900° C., and while it is in progress an appreciable excess of carbide over the eutectoid composition is absorbed in the outer portions of the case. The temperature of the furnace is now slowly reduced—over a period of several hours—to a temperature which is not greater than the refining temperature to which the articles will subsequently be submitted, and is not lower than the eutectoid temperature of the steel. The box is maintained at this temperature for some time, and is then removed from the furnace and allowed to cool in air.

The effect of the period of slow cooling on the distribution of carbide in the case can readily be seen. As the temperature falls the solubility of the cementite in the austenite of the steel becomes progressively lowered; those portions which were saturated, or nearly saturated, with carbide at the case-hardening temperature, tend to throw out their excess of cementite, and those containing less carbide tend to approach more nearly their saturation point. Consequently, as cooling continues, carbide must be removed from solution in the outer portions, either by deposition of cementite, or by some other means. Now it is clear that, during this period, diffusion of carbide towards the centre of the mass is able to continue, and the only condition that must be fulfilled in this operation is that the rate of cooling be sufficiently slow for the removal of the carbide by diffusion towards the centre to be sufficient to prevent supersaturation of the case, at any moment, with the precipitation of free cementite—a matter which is very easily determined by one or two trials. It is equally clear that during this period little or no additional carbide will dissolve in the austenite of the steel, for such absorption can only take place as and when the austenite becomes unsaturated with respect to cementite, that is, as the cementite diffuses into the mass. The internal equilibria in the steel are such that they tend to adjust themselves without any considerable influx of additional carbide. The continual tendency for the case to become supersaturated as the temperature falls renders it less able to absorb more carbon, while the counteracting tendency of diffusion into the core, which determines to some extent the rate at which carbide is absorbed, is partially satisfied by the reduction of the concentration in the case itself. The period of falling temperature, therefore, is one in which the main reaction is the more uniform distribution of the carbide which has already been dissolved in the case during the preliminary heating at the higher temperature.

The final temperature in this treatment is of importance, since it largely determines the maximum concentration of carbide which can exist in the case at the end of the operation, and where the concentration in the finished case is required to be approximately that of the eutectoid, the final temperature should approach fairly closely that of the eutectoid transformation. If, however, the final temperature be lower than that at which the refining treatment is to be carried out, and the cooling to that temperature be sufficiently slow, there should not be left in the case an amount of cementite which will not be wholly dissolved during this refining treatment, and the presence of a network in the finished product is impossible.

It is evident that the exact times and temperatures can best be determined for each class of articles by trial, but this is short and simple, and need give no trouble. Some data collected by the authors on this point will be given.

The authors have not taken into account the production of excessive cementite concentration through oscillations in the case-hardening temperature, because they have wished to show that this excess may be produced, especially in nickel steels, when accidental variations of this kind are not present. In any case, the method of using a falling temperature for the final stages of the carburisation is probably the best which could be adopted for removing excess produced in this manner.

PART II.

EXPERIMENTAL AND PRACTICAL.

Among the articles in which cracks had developed during grinding were a variety of forms of gear wheel, made from a nickel steel of approximately the following composition:

	Per Cent.
Carbon	0·12
Silicon	0·17
Sulphur	0·026
Phosphorus	0·006
Manganese	0·59
Nickel	2·30
Chromium	0·11

These gears had been carburised in a mixture of charred leather with 10 per cent. of barium carbonate for a period of ten hours at a temperature of 900° C., after which the box was withdrawn and cooled in air. For refining and rehardening a subsequent reheating to 800° C., followed by oil quenching, was adopted, and after this treatment the mechanical properties of the core and the hardness of the case were perfectly satisfactory. The gears were sent to another firm for grinding, and many of them failed during this operation, through the formation of fine cracks running from the surface into the metal. On cutting sections through the teeth of a number of wheels, and examining them carefully under the microscope, in almost all cases a certain amount of free cementite, arranged in cellular form, was detected at the edges of the teeth. It was not invariably found, and in some cases might have been removed during the grinding process, but it could nearly always be observed. Fig. 2 shows an etched cross-section of a hardened tooth which had failed, in which the presence of excessive cementite is unmistakable.

In view of the fact that free cementite could be found in nearly all the wheels, and that it appeared probable that the method of carburising used would always give a hyper-eutectoid case, the authors conducted some experiments with the object of determining approximately the amount of excess carbide over the eutectoid composition which was formed. In these experiments they have used only the method of microscopic examination. They would have preferred to add to this actual chemical analysis of the case, but in view of the fact that most of the articles concerned were made of alloy steels, in which the actual composition of the eutectoid is not known, they came to the conclusion that the microscopic method, though it is not strictly quantitative, was to be preferred.

In the first place, they took three bars 6 inches long by ¾ inch diameter, of a 2½ per cent. nickel steel, which were passed through holes in the side of a carburising box, and heated in contact with the mixture for 6½ hours at 900° C. The box was then withdrawn, one bar being quenched in oil, another cooled in air, and the third allowed to cool in the box. The structure of the oil-quenched bar, illustrated in Fig. 3, shows a complete absence of free cementite. The bar, which was cooled in air, was martensitic in the case, but a certain amount of carbide had separated, not in network form, but as a series of long thin needles. Air cooling, even on a small bar of this size, is not sufficiently rapid to keep the cementite dissolved. The slowly cooled bar, illustrated in Fig. 4, contained a coarse thick network of free cementite, and the steel of the outer parts of the case was undoubtedly hypereutectoid. It seems fairly certain, then, that the conditions under which carburisation had been carried out were such as to favour the presence of a coarse network of free cementite.

Some experiments were undertaken to ascertain with what rapidity a carbide concentration greater than that of the eutectoid was attained in the case under the normal working conditions. Four small boxes, each containing one bar, 1½ inch diameter, of 3 per cent. nickel steel, were inserted in a furnace at 900° C.; these were removed at intervals of one, two, three, and four hours respectively, after the furnace temperature had been attained, and allowed to cool in air. Sections were carefully cut and examined. In the bar which had been treated for one hour no excess of carbide was found. In the bar which had been at 900° C. for two hours a carbide network was present in appreciable quantity, and this quantity increased progressively as the length of carburising became increased. It is evident, then, that a high concentration of carbide in the peripheral layers is reached relatively rapidly—in a time, in fact, which is less than any normal commercial carburising operation, and while the actual depth of the case is quite small.

Experiments were then undertaken on this steel, to determine whether the treatment outlined in the earlier part of this paper, of submitting the steel to a slowly falling temperature during the later stages of the carburisation, would give a case in which the harmful cementite network was not found.

Pieces of the 2½ per cent. nickel steel were heated in contact with the carburising material for 6½ hours at a temperature of 900° C., at the end of which time, as has been shown, there is a high concentration of carbide in the outer portions of the case. The temperature was then gradually reduced to 800° C., the refining temperature of the core, which temperature was reached in 4½ hours, and was maintained for a further four hours, the total length of the whole operation being fifteen hours. It was found that by this treatment a depth of case was obtained equal to that formerly obtained by ten hours' heating at 900° C. These times were arrived at after a few preliminary experiments. The specimen was then cooled in the box, which was removed from the furnace.

Microscopic examination showed that this treatment had been very successful. The outer portions of the case contained in no part more than a slight cementite network, as illustrated in Fig. 5. The superiority of this structure is apparent, and on quenching the steel from 800° C. it was found that no cementite was left undissolved, and the structure consisted of a uniformly fine martensite. Fig. 6 illustrates this structure.

In other cases the lowering of the temperature from 900° C. was slower; in many operations on a works scale the whole period of 8½ hours was taken for this lowering, when the box was withdrawn without further treatment, with results which were quite satisfactory. Annealing for one or two hours at the lower temperature, however, appears to give a case slightly lower in carbon than a treatment in which the box is removed immediately 800° C. is reached, but in all the cases examined no free cementite was found after the articles had been hardened.

More recently the authors have carried the reduction of temperature somewhat further. In the above cases the final temperature has been that of the refining operation. In their later experiments, and in routine operations on a large scale, this final temperature has been reduced to a point between the refining temperature of the core and the hardening temperature of the case. In articles made from a 3½ per cent. nickel steel, the falling temperature treatment has been carried out from 900° C. to 740° C. in the same time of 8½ hours, and the results have been entirely satisfactory. A case in 3½ per cent. nickel steel obtained by carburising at 900° C. for 6½ hours and from 900° C. to 740° C. in 8½ hours, followed by cooling in the box, contained in the outer layers mere traces of a cementite network, and a layer of steel of practically eutectoid composition extended from the surface for a distance of 0·05 inch into the steel. Further, the transition from case to core was very gradual, and took place over a distance of 0·03 inch. There was no sign of " liquation " at any point, and indeed the authors have failed to detect any signs of this phenomenon in any of the steels which they have examined after submitting them to this treatment.

This modification of the case-hardening process has been adopted for some months past in the works of D. Napier & Sons, Limited, in all operations on straight carbon and nickel steel parts (except 5 per cent. nickel steel), and has given highly successful results. Many thousands of articles have been treated, and the amount of scrap material has been reduced from at least 25 per cent. to practically nothing. For example, by the old methods of carburising, the scrap in the manufacture of air screw shaft gears from a 2½ per cent. nickel steel amounted to 25 per cent. On adopting the 900° C.–800° C. falling temperature treatment, this was reduced to 2½ per cent. On changing to the 900° C.–740° C. treatment (the steel at the same time being altered to 3½ per cent. nickel), up to the time of writing, out of seventy-five completed gears, none has been found defective. Experience with other forms of gears has been equally satisfactory.

In the manufacture of valve end-pieces from 3½ per cent. nickel steel, out of the first 500 manufactured (by the old method of carburising at 900° C.) at least 25 per cent. were defective. By adopting the 900° C.–740° C. falling temperature treatment, the trouble has disappeared.

With straight carbon steels equally satisfactory results have been obtained. In the manufacture of cam-shafts, for example, the only failures which have been experienced since the modifications were introduced are very small in number, and can, in each case, be traced to excessive non-metallic enclosure in the steel. In every case in which grinding cracks have developed, a sulphur content of over 0·1 per cent. has been found, and microscopic examination has revealed large quantities of sulphide.

It may safely be said that since the introduction of the modifications of the case-hardening process which have been described, troubles from flaking and cracking during and after grinding have become practically unknown, and the very few cases which have occurred can all be connected with material which is otherwise defective.

Note on the Carburising of 5 per Cent. Nickel Steel.

In the case of articles made from 5 per cent. nickel steel, trouble from flaking has never been experienced, in spite of the fact that the usual practice has been to carburise at a temperature of 950° C., a temperature considerably higher than that used for any of the other steels mentioned in this paper, and at least 150° C. above its upper critical point. The authors suggest that the explanation is probably to be found in the fact that this steel, when carburised, is air-hardening, and normal slow cooling in the box is sufficient to suppress the carbide separation, or at any rate to prevent its separation in a harmful form. They have not, however, investigated this steel.

SUMMARY.

1. Ordinary methods of case-hardening at or above 900° C. tend to lead to the formation of a hyper-eutectoid layer in the case, which is a frequent source of flaking and grinding cracks.
2. In nickel case-hardening steel containing up to 3½ per cent. of nickel, the practice of refining at a temperature lower than the carburising temperature tends to aggravate this trouble.
3. Trouble from this cause may be avoided by:
    (*a*) Quenching the steel from a temperature at which the excess of carbide is dissolved.
    (*b*) Modifying the treatment during carburising in such a manner that a case of practically eutectoid composition is obtained.

PLATE XXI.

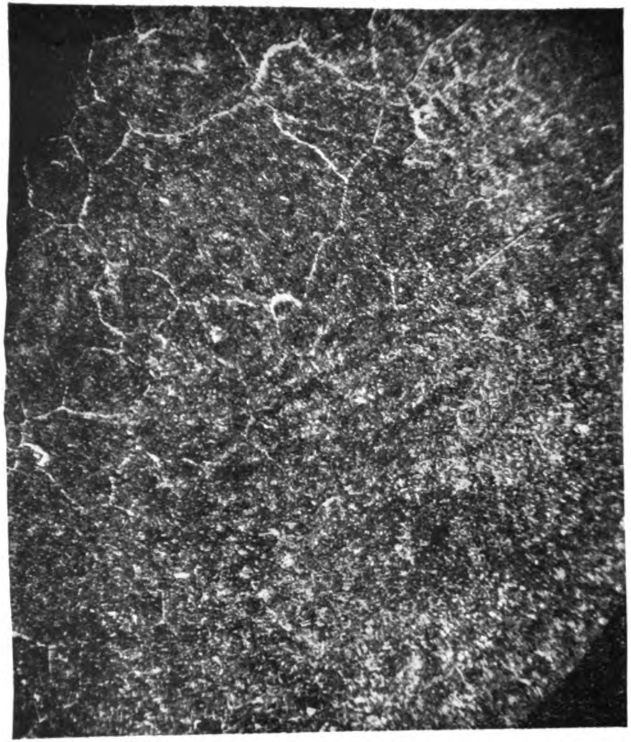

Fig. 2.—Case in 2½ % nickel steel, carbonised at 900°C. and hardened at 800°C. ; showing network of free cementite. Etched with 1 % nitric acid in alcohol. × 100 diam.

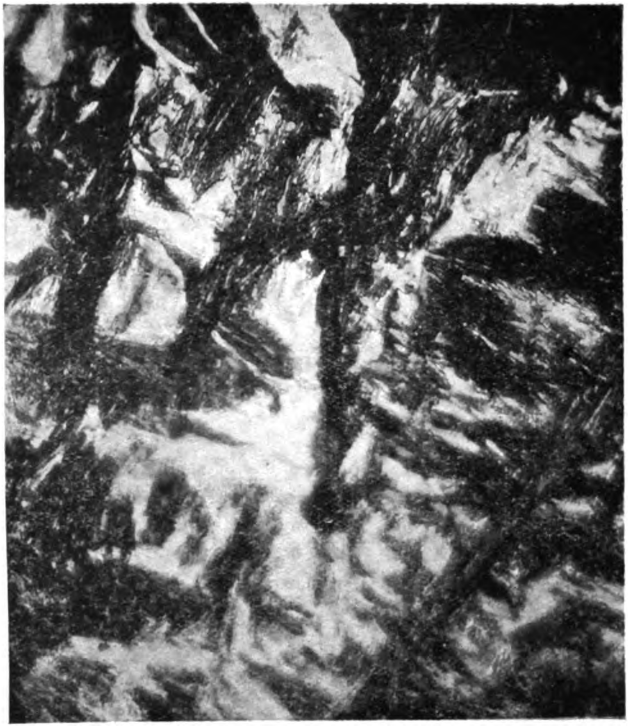

Fig 3.—Case in 2½ % nickel steel carbonised at 900°C. ; quenched from the box, showing coarse martensite only. Etched with 1 % nitric acid in alcohol. × 1000 diam.

To face p. 400.

PLATE XXII.

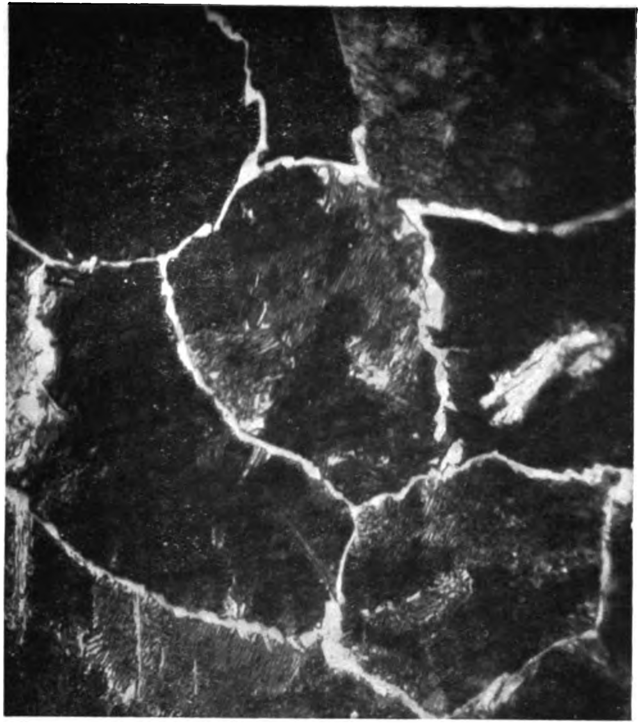

Fig. 4.—Case in 2½ % nickel steel, carbonised at 900°C. and cooled in the box, showing cementite network. Etched in 1 % nitric acid in alcohol. × 1000 diam.

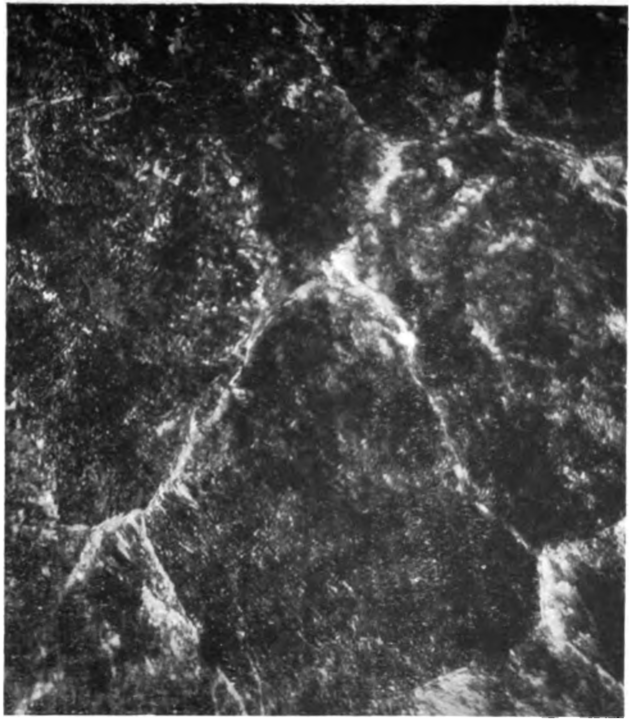

Fig. 5.—Case in 2½ % nickel steel carbonised by falling temperature method; cooled in box, showing slight traces only of cementite network. Etched in 1 % nitric acid in alcohol. × 1000 diam.

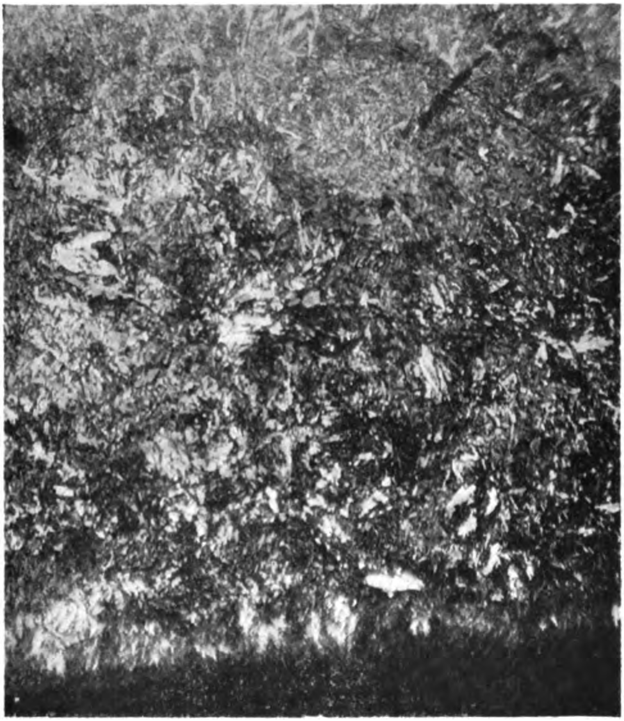

Fig. 6.—Case in 2½ % nickel steel. Same specimen as Fig. 5 after hardening at 800°C. Showing absence of cementite network. Etched in 1 % nitric acid in alcohol. × 150 diam.

4. Of these methods (*b*) is to be preferred.

5. A simple modification of existing practice has been suggested by means of which this can be effected.

6. Experimental evidence and an account of the successful working of the process on a works scale have been given.

7. For 5 per cent. nickel steels a high carburising temperature appears to be satisfactory.

DISCUSSION.

Dr. W. Rosenhain, F.R.S. (National Physical Laboratory), said the method of avoiding the presence of a cementite network in the finished case-hardened product which the authors advocated was an excellent one, provided it was carried out in as careful and scientific a manner as was requisite, because the process of slow cooling from the casing temperature round about 900° C. brought with it very obvious disadvantages. It was well known that slowly cooling steel through that range was not at all a desirable proceeding unless that steel was going to be thoroughly refined afterwards, but provided that was done, as the authors of course naturally would do, the method was a very excellent one. The only criticism that might be offered with regard to it was that it made the very careful carrying out of the method more important than ever. Perhaps that was an advantage, because if it were done badly there was such a bad result that one would not attempt to use it, or the attempt would not last very long. Case-hardening had been a difficulty, not to say a sore subject, during the last four or five years. There had been a very large amount of failure on the part of a number of firms and individuals working at it. The results described in the paper were obtained in an effort to help not only the particular individuals who were concerned, but the whole of the case-hardening industry, over what was a very appreciable difficulty, and he had reason to know that that help had been satisfactory in its results over quite a considerable area. The whole theory of the subject was perhaps a little complicated, but the presentation of it given in the paper, provided it was read very carefully, was, he believed, perfectly sound. When such terms as "saturation temperature" were used it was necessary to read very carefully indeed, otherwise one was apt to be misled.

The alternative method of dealing with case-hardened articles was of course, as Mr. Hanson said, to quench them from the casing temperature, and he thought there were reasons in favour of doing that when the objects were sufficiently small to be emptied out of the casing-boxes into water. In the case-hardening of such things as chain rollers, that was the usual practice and led to very satisfactory results, because by rapid cooling from the temperature at which the carbide had been formed its separation in passing through the critical range was prevented and thus the desired object attained. It was then necessary to reheat to just above the lower critical point and quench again in order to get satisfactory hardening. Of course when it came to a motor lorry gear and larger parts of that kind, quenching straight from the case-hardening box was practically out of the question, because those parts were usually quenched in oil, and it would hardly do to empty the case-hardening material into the oil together with the goods. The oil would very rapidly deteriorate under that kind of treatment and the method was not really practicable. It was in handling the heavier articles particularly that the methods described by the authors would prove, and had proved, very successful.

Dr. F. **Rogers** (Sheffield) said there were two distinct schools of opinion as to whether the carbon in a case should exceed the eutectoid composition or not. In his experience good cases were found amongst both those which were eutectoid and those which were hyper-eutectoid; but many of the troubles which he had encountered in investigations were due to the fact that hyper-eutectoid cases had not been appreciatively heat treated. It was possible to get all or most of the carbide in the case into solution in a hyper-eutectoid carbon steel, by quenching from about the SE line, and it was most commonly claimed that this gave the hardest case. The authors proposed to diffuse the carbon in excess of eutectoid composition inwards, and produce a eutectoid case. They proposed to do this by cooling slowly from SE to PS. He suggested that it would save time to hold the temperature at the carburising temperature, and did not see that anything was to be lost in consequence. The piece could then be quenched or cooled off in whatever way was specially suitable, but as rapidly as possible for all steels which were not air-hardening. The subsequent refining and hardening operations were the same in any event. In practice there would be a saving of time amounting to probably two-thirds of the time occupied by the authors' method of slow fall of temperature. The tendency to cracking in such quenching could be provided against in several ways, which were possibly sufficiently well understood not to require detailed reference on that occasion. His (Dr. Rogers') suggestion provided for cases in which the diffusion of carbon down to eutectoid composition might not occur completely; he would at least have the carbide all in solution.

Mr. C. H. **Smith** (Chelmsford) wished to join issue with the authors over their statement that free cementite was the principal cause of cracking in the grinding. He had seen carburised parts with very great excess of free cementite extending deeply into the case which did not crack on grinding, and he would suggest that that cracking was chiefly a mechanical trouble and could be overcome by suitable grinding. The chief objection that he had to the process described was the increased length of time necessary. He thought that if the cementite were once formed in the skin and the temperature then dropped to the refining temperature—as it might be called—a great deal of time could be saved, as the rate of diffusion of carbon towards the core would then be accelerated. He had, in fact, done work in that direction in which he had obtained the same results, as regards depth, in an equal time as with the ordinary method of carburisation, and a clean case, showing no cementite network. On p. 400 the authors said that in every case in which grinding cracks had developed a sulphur content of over 0·1 had been found. He thought it would be incorrect to assume that the high sulphur content was always present or was the cause of the cracking. The grinding cracks were purely mechanical, and the free cementite had really very little relation to them if the heat treatment subsequent to carburising was satisfactory, although it assisted the development of the crack once it was started. If there were no crack in the heat treatment and the grinding were correctly done, there should be no cracking.

Insufficient emphasis and attention was generally given to keeping the carburising temperature absolutely steady, as fluctuations were largely responsible for the "freckle" which the case-hardener sought to avoid. For that reason the use of ordinary coal-fired furnaces was to be deprecated as a zigzag galvanometer curve corresponding to the stoking was inevitable. It would be extremely difficult, if not commercially impossible, to maintain the requisite steadiness of temperature of the work itself (not the thermocouple) in all parts of the furnace throughout the gradual cooling described by the authors.

Messrs. **Hanson** and **Hurst**, replying to the discussion, wrote that they fully appreciated the necessity for carrying out case-hardening operations in a careful and scientific manner. The slow cooling of case-hardened articles through the critical range was dangerous because it gave opportunity for the separation of the ferrite of the core, at the inner boundary with the case, in massive form. They thought, however, that if their method were carried out as indicated in the paper, the danger of that free ferrite persisting in the finished article was small, since their rate of cooling was sufficiently slow to enable diffusion of the carbide to take place into the first separated ferrite. With regard to the use of the word "saturated," that had a definite meaning in scientific literature, and it was in that sense that it had been used in the paper. The fact that it was frequently used by some workers in a wrong sense appeared to be an insufficient reason for refraining from using it. The authors thought that if Dr. Rosenhain would read the paper carefully he would find that the phrase "saturation temperature" was not used. They agreed with Dr. Rosenhain that the method of quenching direct from the boxes, when applicable, was to be preferred for preventing the formation of a network of cementite in the case. The method described was adopted to meet cases in which that quenching could not be applied.

With reference to Dr. Rogers' communication, they thought that sometimes a case of hyper-eutectoid composition might be preferred to one of lower carbon content. The danger with such cases lay, not in the presence of free carbide in the finished product, but in the manner of its arrangement. That could be controlled by heat-treatment. The treatment outlined by Dr. Rogers was, they thought, safe only if the carburising temperature did not exceed the refining temperature of the core.

Mr. Smith appeared to think that the authors considered that all cases which contained free cementite would crack on grinding. Fortunately for the makers of case hardened parts that was not so, but there was no doubt that steel which contained a network of free cementite was much more liable to that form of failure than steel in which it was not present. No doubt, some improvement could be effected by increased care in grinding, but that did not appear to them to be the best method of overcoming the difficulty. With reference to the slight modification of their process which Mr. Smith had mentioned, they were pleased to note that he had obtained satisfactory results by a prolonged annealing at the refining temperature. Was that not an admission that excessive free cementite might after all be undesirable ? Mr. Smith doubted the authors' statement that certain cases of cracking were associated with high sulphur content in the steel. That was a question of fact on which Mr. Smith was hardly in a position to express an opinion. With regard to the possibility of working the process on a practical scale, they could do no more than ask Mr. Smith to read their paper again, when he would find that it had been in operation for some considerable time, and had given excellent results.

THE MOLECULAR CONSTITUTIONS OF HIGH-SPEED TOOL STEELS AND THEIR CORRELATIONS WITH LATHE EFFICIENCIES.

BY JOHN OLIVER ARNOLD, D.MET., F.R.S., DEAN AND PROFESSOR OF METALLURGY, AND FRED IBBOTSON, B.SC., F.I.C., SENIOR LECTURER IN METALLURGICAL CHEMISTRY OF THE UNIVERSITY OF SHEFFIELD.

WITH A NOTE BY F. C. THOMPSON, D.MET., B.SC.,
ASSISTANT LECTURER IN METALLURGY.

INTRODUCTION.

THE exact determination of the complex chemical constitutions of high-speed steels seemed ten years ago to be shut up in a scientific citadel which might well defy all attacks made upon it by the metallurgical chemist. It was, however, certain that any such assault must be preceded by a series of patient sapping operations carried out to ascertain the forms of existence of the elements of high-speed steel when present singly in quantities ranging say from about 2·5 to 25 per cent. in iron containing say 0·7 per cent. of carbon. Consequently about 1909 one of the authors and Professor A. A. Read, D.Met., F.I.C., of the University of Wales, commenced a series of experiments to ascertain the compositions of the carbides of chromium, vanadium, tungsten, and molybdenum, existing in plain carbon steel containing in addition only a single alloying element.[1]

CONDENSED RESULTS AND BIBLIOGRAPHY OF PRELIMINARY RESEARCHES BY ARNOLD AND READ.

Chromium.—In a series of seven rolled and annealed crucible steel bars, varying in carbon from 0·64 to 0·88 per cent., and in chromium from 0·65 to 23·7 per cent., it was found that, in addition to carbide of iron (Fe_3C) always present, there also existed two distinct carbides of chromium corresponding to the formulæ Cr_3C_2 and Cr_4C, identical with those discovered by Moissan in pure crystals in the electric furnace. In the two lowest chromium steels the topaz-hard carbide Cr_3C_2 was isolated, whilst in the two medium chromium steels a mixture of Cr_3C_2 and the quartz-hard carbide Cr_4C was discovered, but in the highest chromium alloys only Fe_3C and the latter carbide was found. In the four lower chromium alloys no evidence of the existence of a true double carbide of iron and chromium was observed, but in the three highest alloys, ranging from 15 to 24 per cent. chromium, a true double carbide, corresponding to the formula ($2Fe_3C$, $3Cr_4C$) was obtained.[1]

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[1] The authors greatly regret that urgent military duties should have compelled Major Read, R.A., to retire from the research just before the culminating experiments embodied in the present memoir were commenced.

Vanadium.—In a set of five rolled and annealed bars containing from 0·6 to 1·1 per cent. carbon, and from 0·71 to 13·45 per cent. vanadium, a mechanical mixture of Fe_3C and the vanadium carbide V_4C_3 was isolated. With about 4·8 per cent. vanadium present only V_4C_3 was found, the carbide of iron having been completely displaced. It was also found that the transformation of vanadium pearlite ($72Fe + V_4C_3$) to vanadium hardenite ($72Fe, V_4C_3$) took place somewhat abruptly at about 1400° C., hence true vanadium steel containing say about 1 per cent. carbon, even when suddenly quenched from 1300° C., is quite soft to the file. When quenched from 1400° C. the hardenite produced is nearly as hard as corundum.[2]

Tungsten.—In a series of six rolled and annealed crucible steel bars containing from 0·67 to 0·73 per cent. carbonand 2·36 to 26·29 per cent. tungsten, there was isolated from the lower tungsten steels a mixture of Fe_3C and WC, but when about 11·5 per cent. tungsten was present the Fe_3C was completely displaced and carbide of tungsten, WC, was alone obtained. Above 12 per cent. tungsten there was found a mixture of WC and tungstide of iron, Fe_2W. The transformation of tungsten pearlite ($26Fe +$ WC) to tungsten hardenite (Fe_{26}, WC) takes place progressively over a range of about 250° C., namely, say, from 850° to 1100° C.[3]

Molybdenum.—A series of five rolled and annealed bars containing 0·71 to 0·82 per cent. carbon, and from 2·43 to 20·7 per cent. molybdenum, yielded on electrolysis a mixture of Fe_3C with a most remarkable non-magnetic carbide of iron and molybdenum, but when between 18 and 19 per cent. of molybdenum was present the Fe_3C was entirely displaced and the stable true double carbide Fe_3Mo_3C only was obtained. The pearlite of true ferro-molybdenum steel ($24Fe + Fe_3Mo_3C$) transforms to its hardenite (Fe_{24}, Fe_3Mo_3C) in a manner similar to the transformation of true tungsten steel.[1]

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[1] *Journal of the Iron and Steel Institute*, 1911, No. I. p. 249 *et seq.*

[2] *Ibid.*, 1912, No. I. p. 215 *et seq.*

[3] *Proceedings of the Institution of Mechanical Engineers*, 1914, March 20, p. 223 *et seq.*

PART I.

THE CHEMICAL CONSTITUTIONS OF HIGH-SPEED STEELS.

For the present research a set of 36 lbs. ingots, representative of six types of high-speed steel, were melted in white crucibles with coke fuel. The alloys were cast into 2-inch square ingots, which were hammered down into bars 1⅛ inch by ⅝ inch, and "file" annealed by heating the bars during a period of about eight hours till a temperature of nearly 800° C. was attained. They were kept at this temperature for about an hour, and cooled down during a further period of about twenty-four hours. The annealed bars were subsequently forged into turning tools and machined into standard carbide test-bars.

The analyses of the drillings, taken with the usual precautions from the six annealed bars, are embodied in Table I.

TABLE I.—*Mean Analyses per Cent. of closely-agreeing Duplicate Determinations.*

Crucible Cast Steel No.	C.	Cr.	W.	Mo.	V.	Si.	S.	P.	Mn.
1574	0·75	2·79	absent	5·79	1·29	0·47	0·061	0·016	0·18
1575	0·72	2·79	"	5·72	absent	0·41	0·061	0·015	0·18
1576	0·76	2·82	12·12	2·06	1·28	0·60	0·059	0·015	0·19
1577	0·62	2·79	12·00	2·06	absent	0·43	0·060	0·016	0·20
1578	0·55	2·62	15·93	absent	1·16	0·34	0·058	0·017	0·20
1579	0·60	2·78	15·54	"	absent	0·44	0·058	0·016	0·21

OUTLINE OF RESEARCH SCHEME.

An inspection of Table I. will show that throughout silicon contents of 0·4 per cent. were aimed at, the manganese was calculated for 0·2 per cent., the phosphorus for 0·015 per cent., and the sulphur at the lowest possible contents of 0·06 per cent. (The specification makers have demanded sulphur of 0·02 per cent., indicating that makers of steel specifications are not necessarily steel metallurgists.) With reference to carbon, 0·65 per cent. was aimed at with an unavoidable plus or minus difference of 0·1 per cent. With reference to the real alloying elements of high-speed steel, it was aimed to keep the chromium constant throughout the series between 2·7 and 3 per cent. Two tungsten contents were aimed at, namely, a low limit of 12 per cent. and a medium limit of 16 per cent. To one medium tungsten steel no vanadium was added; in the other, and indeed in all the steels in which vanadium was present, the mixes were calculated to melt out with 1·25 per cent. vanadium. To one of the 12 per cent. tungsten steels no vanadium and 2 per cent. molybdenum was added. In the second 12 per cent. tungsten steel the aim was to introduce 2 per cent. molybdenum and 1·25 per cent. vanadium. In one steel tungsten and vanadium were designed to be absent, being replaced by 6 per cent. of molybdenum. In the final ingot the 6 per cent. molybdenum was supplemented by the designed addition of 1·25 per cent. vanadium. Thus, even with only six types of high-speed steel, the authors had assigned to themselves probably the most complex problem in the metallurgical chemistry of steel ever attempted, and, to be quite candid, it must be confessed that at the outset no one was more dubious than they as to the probability of success.

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[1] *Proceedings of the Institution of Mechanical Engineers*, 1915, November, p. 629.

ELECTROLYTIC DIFFERENTIAL ANALYSES OF THE CARBIDES AND TUNGSTIDE.

The method used and the apparatus employed for the electrolytic separation of the carbides were substantially those which have been described for tungsten carbide,[1] using a hydrochloric acid electrolyte of specific gravity 1·02 with a current density of 0·18 ampere per square inch of anode throughout. The time of immersion in the electrolyte (for each bar) was, however, 15 instead of about 1½ hours. The results are set forth in Table II.

The approximate percentages of the totals of the vital elements present and found in the carbide and tungstide residues are embodied in Table III., being, of course, calculated from Tables I. and II.

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[1] *Proceedings of the Institution of Mechanical Engineers*, 1914, March 20, p. 233 *et seq.*

TABLE II.—*Analyses of the Carbides and Tungstide Residues from Steels Nos.* 1574 *to* 1579 *inclusive.*

Steel No.	Weight (Grammes) of Steel Dissolved.	Weight (Grammes) of Residue Obtained.	Percentage Compositions.							
			Carbon.	Iron.	Chromium.	Tungsten.	Molybdenum.	Vanadium.	Totals.	Mean Impurities by Difference.[1]
1574	11·1350 11·1550	1·5589 1·5949	5·04 5·00	39·66 39·44	10·64 10·68	absent ,,	35·28 35·44	6·99 6·92	97·61 97·48	2·45
1575	8·3378 8·3158	1·3383 1·3282	4·11 4·19	48·04 48·09	10·81 10·64	absent ,,	33·57 33·44	absent ,,	96·53 96·36	3·55
1576	8·8624 8·8800	2·1575 2·1602	3·06 3·05	29·08 29·30	6·42 6·46	46·14 46·08	7·74 7·81	4·58 4·50	97·02 97·20	2·89
1577	9·3176 9·3484	2·0490 2·0582	2·68 2·72	32·42 32·16	7·20 7·24	46·21 46·34	8·42 8·53	absent ,,	96·93 96·99	3·04
1578	8·7718 8·9466	2·0124 2·0426	2·33 2·32	23·96 23·62	3·13 3·13	64·24 64·62	absent ,,	4·68 4·81	98·34 98·50	1·58
1579	9·5638 9·5934	2·5068 2·3182	2·46 2·48	29·32 29·48	6·84 6·82	58·78 58·71	absent ,,	absent ,,	97·40 97·49	2·55

[1] Consisting mainly of hydrated SiO_2 (+ roughly 0·2 per cent. manganese existing as Mn_3C). See Arnold and Read's paper on "The Chemical Relations of Carbon and Iron," *Journal of the Chemical Society*, 1894, p. 794.

NOTE.—For the analytical methods employed to obtain the results embodied in the above Table II., see Appendix I., p. 424.

TABLE III.—*Approximate Percentages of the Total Elements present in the Six Steels in the Electrolytically isolated Carbides and Tungstide Residues.*

Steel No.	C.	Cr.	W.	Mo.	V.
1574	93·69	53·50	absent	85·29	75·86
	94·97	54·86	,,	87·54	76·72
1575	91·54	62·20	absent	94·21	absent
	92·83	60·92	,,	93·37	,,
1576	97·88	55·51	92·68	91·45	87·12
	97·50	55·82	92·49	92·23	85·53
1577	95·81	56·74	84·67	89·86	absent
	97·38	57·14	85·04	91·16	,,
1578	96·68	27·40	92·45	absent	92·53
	95·79	27·27	92·53	,,	94·64
1579	98·86	59·34	91·22	absent	absent
	99·88	59·29	91·33	,,	,,

In Table IV. are embodied, as the result of calculations made from Table II., the mean analyses of the carbides on a 100 per cent. basis.

TABLE IV.

Steel No.	C.	Fe.	Cr.	W.	Mo.	V.
1574	5·15	40·54	10·92	...	36·24	7·13
1575	4·30	49·82	11·12	...	34·73	...
1576	3·15	30·06	6·63	47·49	8·01	4·67
1577	2·78	33·31	7·45	47·73	8·74	...
1578	2·36	24·17	3·18	65·46	...	4·82
1579	2·53	30·16	7·01	60·29	...	...
Atomic weights .	12	56	52	184	96	51

From Table IV. have been obtained, by the usual calculations, the atomic relationships embodied in Table V. From

TABLE V.

Steel No.	C.	Fe.	Cr.	W.	Mo.	V.
1574	0·429	0·724	0·209	...	0·378	0·140
1575	0·358	0·890	0·213	...	0·362	...
1576	0·262	0·537	0·127	0·258	0·083	0·092
1577	0·232	0.595	0·143	0·259	0·091	...
1578	0·197	0·432	0·061	0·356	...	0·095
1579	0·211	0·539	0·134	0·328	...	...

the values set forth in Table V., by the tedious plan of "trial" calculations and also by the more scientific methods of algebraic calculations, have been determined the chemical constitutions tabulated in the second column of Table VI.[1]

The constitutional formulæ set forth in the second column of Table VI. confirm in a remarkable manner the accuracy of the former researches of the authors and Read, in which only single elements were investigated and the formulæ of their carbides deduced. Every one of the constituents discovered in these earlier researches appears in high-speed steels even when all four alloying elements are present, with the single exception of the topaz-hard carbide Cr_3C_2. It is, however, not surprising that this constituent is absent when it is remembered that the carbon present, in addition to the claims of chromium, has to satisfy the affinities for carbon of vanadium, tungsten, and molybdenum. It will be seen that in some cases all three elements, in addition to the chromium and iron, have seized their shares of carbon. When it is realised that Cr_3C_2 contains about 13·4 per cent. carbon and Cr_4C requires only about 5·4 per cent., it becomes clear that insufficient carbon was left to form the higher carbide, and that therefore only the lower compound was produced throughout. This fact disproves the theory formerly held by one of the authors, namely, that the chromium in high-speed steels containing about 3 per cent. chromium probably always existed as Cr_3C_2. Also another theory held by the same author that all high-speed steels contained no Fe_3C falls to the ground, as this is true only when high tungsten and vanadium are present together. In this connection it may be noted that a peculiar feature of the table is that only in steel No. 1578 is Fe_3C absent. The reason for this is clear. This steel contains about 16 per cent. tungsten and nearly 1·2 per cent. vanadium (in addition to 2·6 per cent. chromium), and the presence together in one steel of such high proportions of tungsten and vanadium has caused these elements to appropriate the carbon to such an extent as to leave none available to produce carbide of iron, since any carbon left, after satisfying the tungsten and vanadium, has

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[1] In connection with this table the algebraic methods used for calculating the formulæ, data having reference to the abrasive hardness of the various carbides, hardenites, and tungstide of iron, the carbon contents of the various carbides, and also the percentage composition of the tungstide, are given in Appendix III., p. 427.

TABLE VI.

Steel No.	Molecular Constitutions and Formulæ of the Isolated Carbides (and, when present, Tungstide).	Percentage Compositions.							
		Elements.	C.	Fe.	Cr.	W.	Mo.	V.	A.E.[1] Per Cent.
1574	$9Fe_3C + 4Cr_4C + 3V_4C_3 + 10Fe_3Mo_3C$	Analytically registered	5·15	40·54	10·92	absent	36·24	7·13	1·66
		Theoretical	4·86	40·40	10·53	,,	36·46	7·75	...
1575	$10Fe_3C + 3Cr_4C + 7Fe_3Mo_3C$	Analytically registered	4·30	49·82	11·12	absent	34·73	absent	0·80
		Theoretical	4·19	49·79	10·88	,,	35·15	,,	...
1576	$10Fe_3C + 8Cr_4C + 6V_4C_3 + 7Fe_3Mo_3C + 23WC + 42Fe_2W$	Analytically registered	3·15	30·06	6·63	47·49	8·01	4·67	0·38
		Theoretical	3·14	29·98	6·60	47·43	7·99	4·85	...
1577	$10Fe_3C + 6Cr_4C + 16WC + 5Fe_3Mo_3C + 27Fe_2W$	Analytically registered	2·78	33·31	7·45	47·72	8·74	absent	0·35
		Theoretical	2·68	33·42	7·52	47·70	8·69	,,	...
1578	$2Cr_4C + 3V_4C_3 + 16WC + 30Fe_2W$	Analytically registered	2·36	24·17	3·18	65·46	absent	4·82	0·84
		Theoretical	2·46	25·50	3·16	64·24	,,	4·65	...
1579	$3Fe_3C + 2Cr_4C + 8WC + 12Fe_2W$	Analytically registered	2·53	30·16	7·01	60·29	absent	absent	0·23
		Theoretical	2·56	30·30	6·82	60·32	,,	,,	...
Notes.—Cr_3C_2 absent throughout. Fe_3C absent only from 1578.		Atomic weights used	12	56	52	184	96	51	...

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[1] Sum of the accumulated errors of analysis, both plus and minus, in determining the four, five, or six elements present.

been annexed by the chromium. It is more than probable that the order of intensity of affinity for carbon of the five alloying elements present in the series is (1) vanadium, (2) molybdenum, (3) tungsten, (4) chromium, and (5) iron. (See Appendix IV.)

MICROGRAPHIC ANALYSIS.

The correlation of the micrographic with the chemical analysis, though broadly clear, is somewhat general, and leaves the exact nature of the constituents revealed considerably in the region of surmise. It was found that four half-sections would sufficiently well represent the types of structure presented by all the twelve microsections examined. Six of these were taken from the well-annealed bars and a corresponding six were cut into microsections ⅝ inch square by ¼ inch thick, and these were rapidly quenched from 1300° C. in cold water.

Steel No. 1574.

Composition per Cent.	
Carbon . . .	0·75
Chromium . . .	2·79
Tungsten . . .	nil
Molybdenum . .	5·79
Vanadium . . .	1·29

The annealed specimen of this steel shows a pale background of an intermetallic solution overlaid by dark troostitic and paler sorbitic varieties of a pearlite of unknown composition, the whole being overlaid by nodules and streaks of a brilliant white cementite, no doubt a mixture of segregated carbides.

The quenched specimen shows well-marked allotrimorphic crystals of a mixed hardenite, which, here and there, are partially surrounded by a unique dark-etching pearlitic constituent. In all probability this is troostitic vanadium pearlite, which does not transform to its hardenite until heated to 1400° C. (see Micrograph No. 1, Plate I.).

Steel No. 1575.

Carbon . . .	0·72
Chromium . . .	2·79
Tungsten . . .	nil
Molybdenum . .	5·72
Vanadium . . .	nil

The annealed specimen was similar to 1574, but exhibited only nodules of cementite, streaks being absent.

The quenched specimen showed no dark pearlitic areas like those in 1574, but merely allotrimorphic crystals of a mixed hardenite with optically dark boundary lines.

Steel No. 1576.

Carbon . . .	0·76
Chromium . . .	2·82
Tungsten . . .	12·12
Molybdenum . .	2·06
Vanadium . . .	1·28

The annealed specimen was similar to 1575.

The quenched specimen exhibited allotrimorphic crystals of hardenite surrounded with thin cell walls of troostitic pearlite together with fairly thick and very broken cell walls of cementite more or less segregated into nodules (see Micrograph No. 2, Plate I.).

Steel No. 1577.

Carbon . . .	0·62
Chromium . . .	2·79
Tungsten . . .	12·00
Molybdenum . .	2·06
Vanadium . .	nil

The annealed specimen was similar to 1574.

The quenched specimen showed globules of cementite along the junctions of the rather large crystals of hardenite.

Steel No. 1578.

Composition per Cent.	
Carbon	0·55
Chromium	2·62
Tungsten	15·93
Molybdenum	nil
Vanadium	1·16

The annealed specimen was similar to 1575.

The quenched specimen showed the smallest crystals of hardenite observed in the series. These crystals exhibited small nodules of cementite both round the junctions and in the crystals themselves.

Steel No. 1579.

Carbon	0·60
Chromium	2·78
Tungsten	15·04
Molybdenum	nil
Vanadium	nil

The annealed specimen was similar to 1575.

The quenched specimen resembled 1578, except that the hardenite crystals were somewhat larger.

Note.—In none of the specimens was any sulphide detected, although in each section about 0·06 per cent. of sulphur was present. Doubtless this sulphur is in solid solution, either as sulphide of tungsten or sulphide of molybdenum. It has already been pointed out by one of the authors that high tungsten steels will take into solid solution the sulphide of tungsten produced by the presence of over 0·2 per cent. of sulphur in high-speed steels.

ABSORPTION AND RECALESCENCE CURVES.

These curves were obtained substantially as formerly described,[1] but owing to lack of time, because this research had, before publication, to pass the Boards of Censorship, it was impossible to figure all the obtained curves in the present paper. One pair of curves will, however, indicate the general nature of the results recorded. They are plotted in Fig. 1, which reproduces the two curves obtained on the third heating and cooling of steel No. 1574 of this research.

The Absorption Curve.[2]—The absorption curve record, starting at 638° C. (a low red heat), presented the usual absorption line till a temperature of about 800° C. was reached. Here was recorded an absorption of heat (maximum at 812° C.) due to the change of the mixed pearlites of iron and chromium $(xFe_3C + yCr_4C)$ to their mixed hardenites. Then at about 850°, in a progressive series of relatively small absorptions of heat, the

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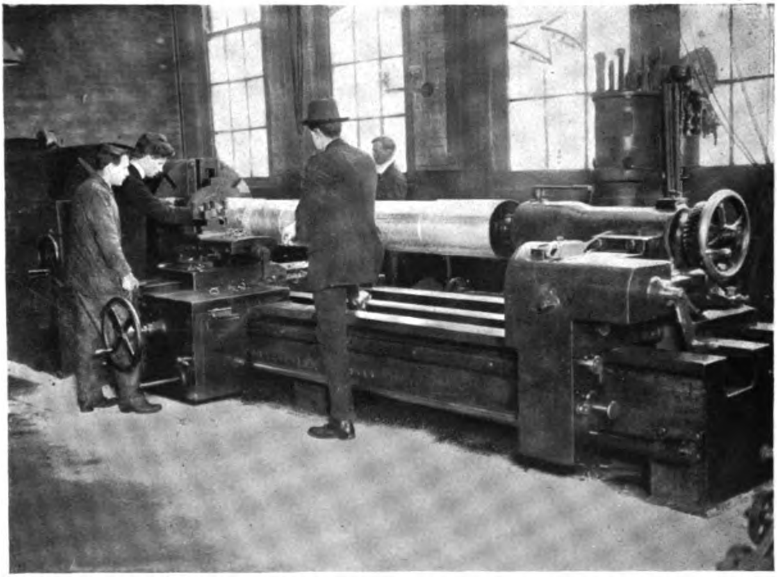
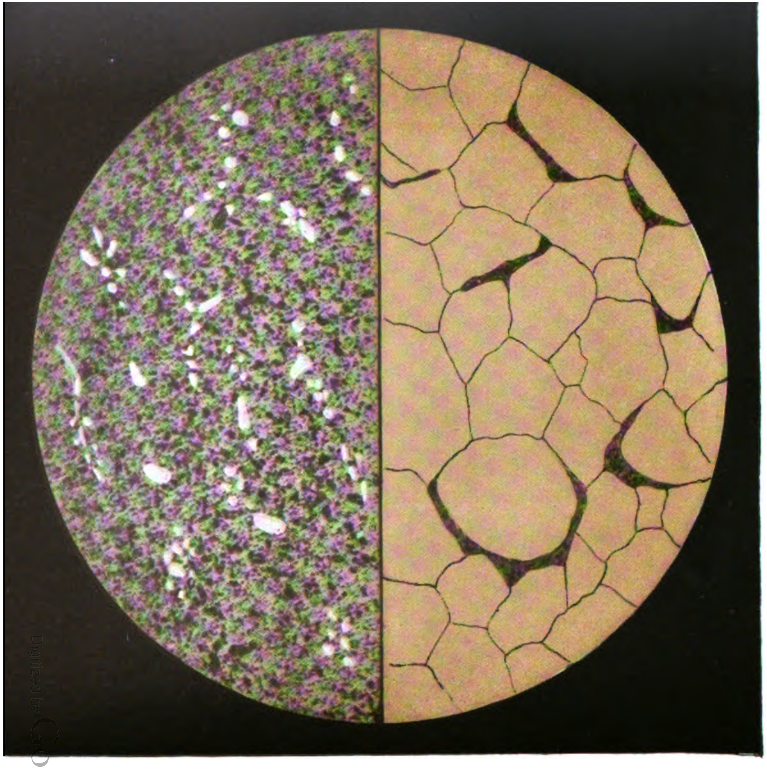
[1] *Journal of the Iron and Steel Institute*, 1894, No. I. pp. 107 to 155 inclusive, and Plates XVIII. and XIX.

[2] An ill-considered proposal has been made to call such curves as this "calescence" curves. Recalescence (the term proposed by Sir William Barrett, F.R.S., in 1872) obviously means "reheating." Therefore "calescence" means heating, which is absurd when cooling is referred to.



40-H.P Electrical Speed Increment Lathe used for testing H.S.S. at Sheffield University.

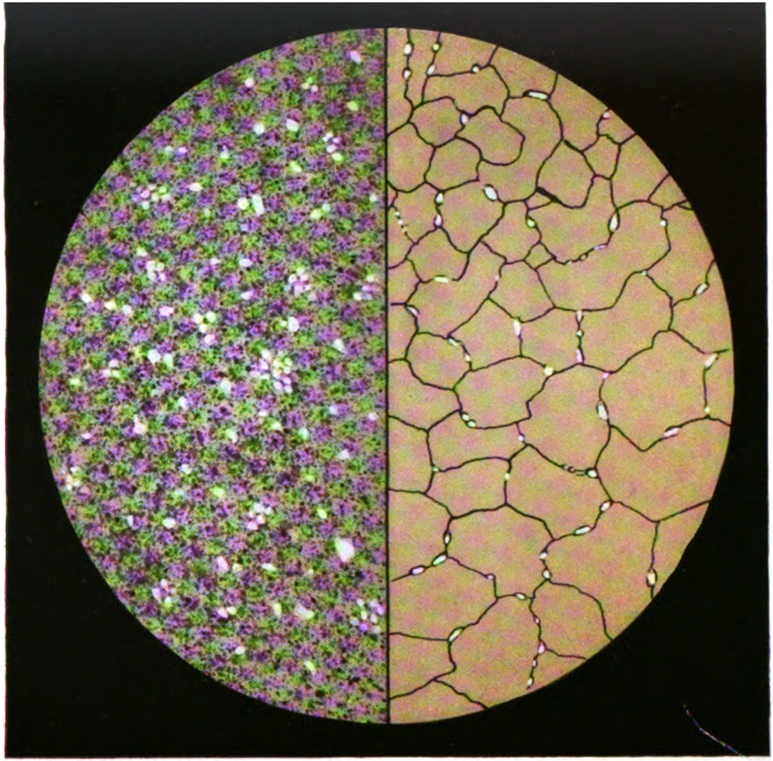


No. 1.—MICROGRAPH.

Steel No. 1574. Left half-section annealed. Right half-section quenched in water from 1300° C.

C 0·75. Cr 2·79. W Nil. Mo 5·79. V 1·29 Per Cent.

Transverse Section. Magnified 750 diameters and reduced from 6″ diam. to 3¾″ diam. Etched in alcoholic picric acid.



No. 2.—MICROGRAPH.

Steel No. 1576. Left half-section annealed. Right half-section quenched in water from 1300° C.

C 0·76. Cr 2·82. W 12·12. Mo 2·06. V 1·28 Per Cent.

Transverse Section. Magnified 750 diameters and reduced from 6″ diam. to 3¾″ diam. Etched in alcoholic picric acid.

tungsten pearlite pursues its transformation to tungsten hardenite, which change is completed in a relatively abrupt and large absorption of heat at somewhere about 1100° C., the maximum of this point presenting itself at 1067° C.[1]

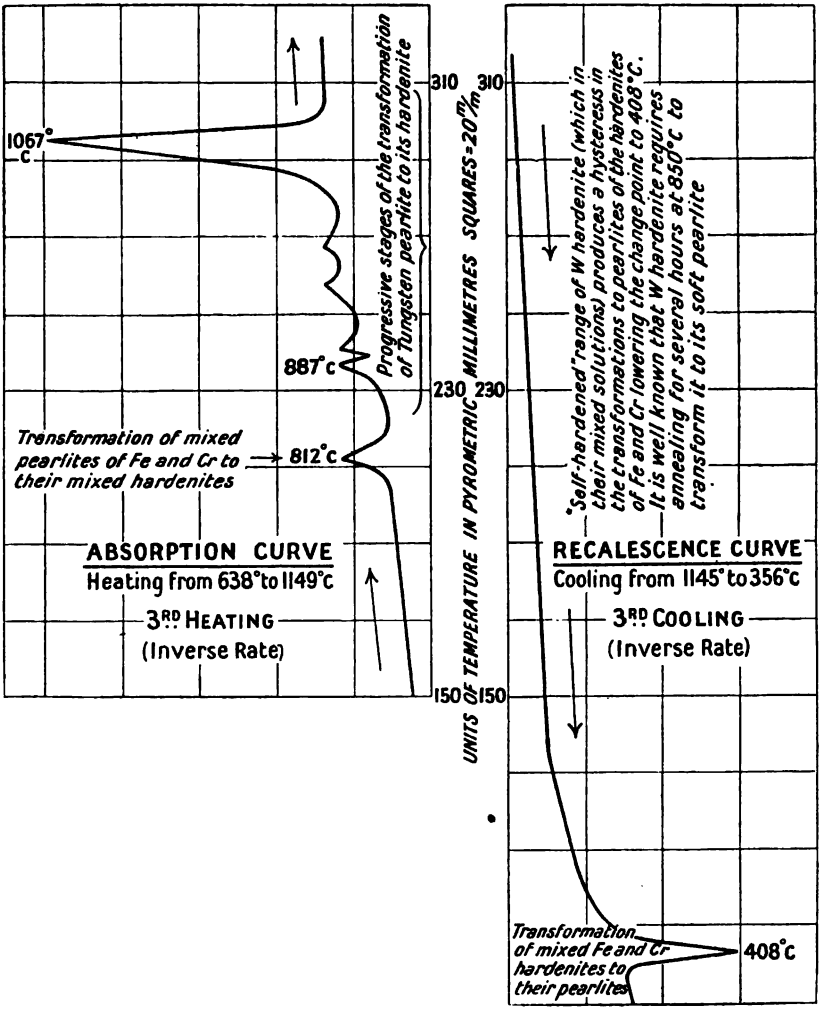


FIG. 1.—Turning Tool No. 1579. C 0·6; Cr 2·8; W 15·9 per cent.

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[1] This curve was predicted by Arnold and Read in 1914. See *Proceedings of the Institution of Mechanical Engineers*, March 1914, pp. 244–5, and p. 408 of present memoir.

The Recalescence Curve.—This curve of the cooling of steel No. 1574 shows the almost ideal radiation line of Arnold's apparatus until a well-marked recalescence, reaching a maximum at 408° C., presents itself. This is the change of the mixed hardenites of iron and chromium to their mixed pearlites. The tungsten hardenite is practically untransformed. (As is well known, high tungsten steel (12 to 18 per cent.), when heated to a yellow-white heat and cooled in air, requires several hours slow cooling, say from 900° C., before it can be drilled.)

PART II.

CORRELATION OF THE CHEMICAL AND MICROGRAPHIC ANALYSES WITH LATHE EFFICIENCIES OF THE SERIES.

Forging, Grinding, and Heat-treatment of the Tools.—The tools were forged at a mellow yellow heat (about 1100° C.), roughly ground, hardened, and finally ground (radius to template) into the shape shown in Fig. 2.

Two schemes of hardening were adopted.

First Method.—The method used by tool smiths in ordinary works practice. The noses of the tools were gradually heated in a coke hearth to a yellowish-white colour (judged by the eye), and were then quenched out in whale oil (odd numbers) or were quenched to a black in warm water and cooled off in a strong compressed air-blast (even numbers).

Second Method.—The noses of the tools were slowly pre-heated in a smith's fire to a bright red colour, and were then raised to a yellowish-white heat in an electrically melted bath of pure barium chloride, pyrometrically controlled at 1300° C. (plus or minus 10°), and quenched out in whale oil (odd numbers) or were quenched in water at about 60° and quickly cooled in a compressed air-blast (even numbers).

Manufacture, Heat-treatment, and Chemical Analysis of Hard Steel Shaft used for Testing Operations.—It was decided to obtain a hard steel shaft of the most even micrographic texture practically possible. An acid open-hearth ingot about 17½ inches square, and weighing about 27 cwts., was therefore cast. This ingot was hammered down to about 13 inches round and allowed to cool on the floor of the forge without any further heat-treatment. About 25 per cent. of the upper end of the open topped ingot was discarded and the shaft, weighing about 1 ton, was turned down to a little under 12 inches diameter before commencing the tests in order to remove the decarburised skin and surface hammer hardness. The mean analysis of the bar was :

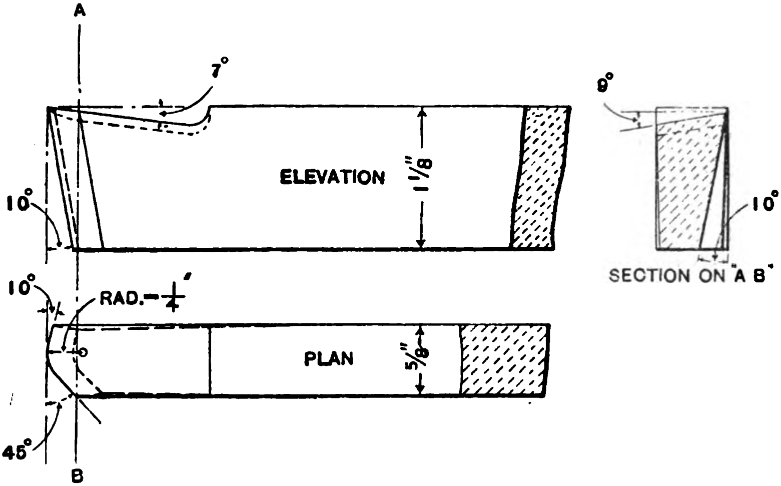

Fig. 2.

	Per Cent.
Carbon	0·960
Silicon	0·120
Manganese	0·850
Phosphorus	0·045
Sulphur	0·044
Aluminium	trace
Iron by difference	97·981

Structure of the Test Bar.—In virtue of its composition this bar naturally presented a very even texture of finely granular manganiferous pearlite.

Segregation Tests.—During turning operations, turnings were taken from each end and midway from the bar, and registered the following analytical figures :

	Carbon per Cent.	Sulphur per Cent.
Driving headstock end	0·96	0·045
Middle of bar	0·94	0·045
Loose headstock end	0·97	0·043

The segregation is, therefore, practically negligible.

Hardness Tests.—A series of hardness figures by the Brinell machine and by the scleroscope were taken from transverse sections of the bar, and it was found that the Brinell values varied from 241 to 269, and the scleroscope figures from 30 to 37. The above records from a ton shaft are not at all unsatisfactory with reference to mean hardness. (See Appendix V.)

The Lathe Methods Employed.—The whole of the tests were conducted without any lubrication on the 40 horse-power electrically driven speed increment lathe used for testing high-speed steel in the Faculty of Metallurgy of Sheffield University. (See Plate XXIV.) The starting speed was increased 1 foot per minute till the tool broke down. When the cutting speed reached well over 30 feet per minute the cutting edge of the tool became red hot, say rather over 600° C., and the small particles of steel occasionally ejected from the test-bar scintillated brightly for a second or so.

The results of the efficiency tests on the steels, together with their dominating alloying elements and other details, are embodied in Table VII.

PRACTICAL AND THEORETICAL DEDUCTIONS FROM TABLE VII.

The comparative efficiencies of the six types of high-speed steels tested in this research are shown in Table VIII. (p. 422) in order of merit as measured by the weight of hard unannealed steel removed during the tests.

A perusal of Table VIII. will render evident the fact that the efficiencies of the three steels containing vanadium (and consequently capable of being water hardened without cracking) have a mean efficiency of 108·9 as against a mean efficiency of only 61·9 obtained from the non-vanadiferous oil-quenched steels. The mean efficiency of the steels hardened from the temperature-controlled University salt bath equals 108·9; that of the steels hardened from the smith's fire equals 102·5.

With reference to the relative hardening power of tungsten and molybdenum, in a paper on "The Chemical and Mechanical Relations of Iron, Molybdenum, and Carbon,"[1] the authors

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[1] *Proceedings of the Institution of Mechanical Engineers*, 1915, November, p. 650.

TABLE VII.—*Results of* 35 *Lathe-tool Tests on Unannealed Hard Steel Bar with Standard Tool Shape* (*see Fig.* 1) *throughout the Trials. Cut* $\frac{3}{16}$ *Inch. Traverse* $\frac{1}{12}$ *Inch. Starting Speed* 20 *Feet per Minute. Speed Increment* 1 *Foot per Minute.*

Tools from Ingot No.	Approximate Percentages of Dominating Alloying Elements.					Durations of Tests in Minutes and Seconds.				Breakdown Speeds in Feet per Minute.				Actual Weights of Steel removed from Test Bar in Lbs.				Method of Quenching. (In Hardening from the Salt Bath the Temperature was about 1300° C. ± 10° C.[3])
	C.	Cr (constant).	W.	Mo.	V.	1st Grinding.	2nd Grinding.	3rd Grinding.	Mean.	1st Grinding.	2nd Grinding.	3rd Grinding.	Mean.	1st Grinding.	2nd Grinding.	3rd Grinding.	Mean.	
1574	0·75	2·79	absent	5·79	1·29	14–26	14–42	15–21	14–50	34·2	34·2	34·8	34·4[2]	18·6	19·0	21·7	19·8	From University salt bath—hot water and air.
						13–18	14–6	12–14	13–13	32·8	33·9	32·3	33·0[2]	17·8	19·1	15·7	17·5	By steelworks tool smith.
1575	0·72	2·79	absent	5·72	absent	7–37	7–8	Tool broke	7–23	26·8	27·2	Tool broke	27·0	8·9	8·6	Tool broke	8·8	From University salt bath—cool whale oil.
						7–37	9–11	8–41	8–30	27·0	28·8	28·0	27·9	8·8	10·9	10·4	10·0	By steelworks tool smith.
1576	0·76	2·82	12·12	2·06	1·28	14–58	14–6	12–59	14–1	34·0	34·0	32·0	33·3[2]	20·1	18·6	17·0	18·6	From University salt bath—hot water and air.
						11–40	12–7	9–8	10–58	31·0	32·0	29·2	30·7	14·1	15·0	11·0	13·4	By steelworks tool smith.
1577	0·62	2·79	12·00	2·06	absent	12–3	10–21	9–36	10–40	31·8	30·0	28·8	30·2	15·0	12·9	11·4	13·1	From University salt bath—cool whale oil.
						11–13	10–30	7–20	9–41	31·2	29·9	27·3	29·5	13·9	13·1	8·6	11·9	By steelworks tool smith.
1578	0·55	2·62	15·93	absent	1·16	15–2	13–33	11–28	13–21	35·0	33·2	31·0	33·1[2]	20·2	17·9	14·9	17·7	From University salt bath—hot water and air.
						16–1	14–19	11–20	13–53	35·8	34·0	31·2	33·7[2]	22·6	19·8	14·4	18·9	By steelworks tool smith.
1579[1]	0·60	2·78	15·54	absent	absent	9–58	8–52	7–27	8–46	28·8	28·2	27·2	28·1	12·6	10·8	8·5	10·6	From University salt bath—cool whale oil.
						11–6	8–37	8–42	9–28	31·2	28·2	28·0	29·1	13·7	10·6	10·5	11·6	By steelworks tool smith.

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[1] Up to about 1906–7 this was the type of the best high-speed steel on the market. About this date it was surpassed by steel of the type exemplified in No. 1578.

[2] Cutting edge of tool red hot.

[3] Pyrometers employed: (1) Foster (base metal immersed thermo-couple); (2) Mesuré and Noël (polarised light); (3) Leskole (spectroscopic; modified Wanner). "Black body" conditions for the optical pyrometers obtain in the hardening shop at Sheffield University, and the readings of all three pyrometers were taken simultaneously and independently by senior undergraduates under supervision by the Senior Lecturer on Pyrometry.

showed that the theoretical hardening powers of molybdenum and tungsten in high-speed steel were respectively about 2·3 to 1. In the present research, however, it has been found that when, say, 1·25 per cent. vanadium is present, this hardness factor becomes greater, being, instead of 2·3, about 2·7. Thus assuming (to avoid any exaggeration) that steels 1574 and 1578 are practically equal in cutting efficiency, then 5·79 per cent. molybdenum is equivalent to 15·93 per cent. tungsten, but 15·93 divided by 5·97 equals 2·68 nearly. On this basis, taking steel No. 1577, the theoretical tungsten equivalent would be 12 + (2·06 × 2·68), which equals 17·5 per cent. tungsten, but the actual mean lathe efficiency of this steel as compared with that of steel 1574 is only 12·5 to 18·6 lbs. of steel removed, hence theoretical hardness and practical lathe efficiency are by no means identical terms, as has been decisively demonstrated by one of the authors.[2] An interesting comparison is found in the mean relative efficiencies of steels Nos. 1574 and 1575, which are respectively 18·6 and 9·4, and owing to the well-known erratic behaviour of molybdenum *per se*, 1575 is the only steel of the whole series which broke in the lathe. Hence about 1·2 per cent. vanadium has prevented water-cracking and raised the cutting efficiency of the steel 98 per cent. Figures closely agreeing with these (101 per cent.) were plentifully proved in connection with chromium-tungsten-cobalt high-speed steel in the semi-private research published by one of the authors about June 1914, and then officially deposited in the archives of Sheffield University.

TABLE VIII.

Steel No.	Efficiency Position.	Type.[1]	No. of Tests.	Lbs. of Steel Removed.
1574	1	V–Mo	six	111·90
1578	2	V–W	,,	109·80
1576	3	V–W–Mo	,,	96·10
1577	4	W–Mo	,,	72·00
1579	5	W	,,	66·60
1575	6	Mo	five	47·00

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[1] Chromium practically constant at about 2·76 per cent.; mean carbon 0·66, plus or minus 0·10 per cent.

[2] *Journal of the Iron and Steel Institute*, 1916, No. I. p. 102.

ACKNOWLEDGMENTS.

In conclusion, the authors have gratefully to acknowledge "grants in aid" of this costly research (which has occupied two and a half strenuous war years) of £250 from Sir Robert Hadfield, Bart., F.R.S., and of £150 from the Council of the Iron and Steel Institute. Without such generous help the investigation could not have been completed in any reasonable time.

The authors have also to tender to their colleagues, for their most efficient and enthusiastic help, their heartiest thanks.

Mr. F. K. Knowles, B.Met., Senior Lecturer in Metallurgy, has, as usual, ably carried out in the University crucible furnaces the production of the complex ingots desired. He also skilfully supervised the pyrometric determinations of the temperatures of the hardening bath and the recording of the inverse-rate absorption and recalescence curves. In these last-named observations Mr. Knowles was most ably assisted by Lieut. R. T. Percival, R.A.F.

Dr. F. C. Thompson, B.Sc., Metallurgist to H.M. Tank Warfare Department, most patiently and accurately reproduced the micrographs illustrating this memoir, and in addition gave the authors valuable assistance in determining from their atomic ratios by the "trial" and "algebraic" methods the molecular constitutions of the six steels.

Additionally in this connection their thanks are also due to Mr. T. G. Elliott, F.I.C., Chief Chemist; Mr. G. B. Willey, A.R.S.M., Chief Assistant Chemist at Messrs. Hadfields Limited; and to Mr. L. Dufty, B.Met., Head Chemist to Sir Joseph Jonas, Colver & Co., Ltd., Sheffield.

They wish also particularly to acknowledge their indebtedness to Mr. G. W. Burley, A.M.I.Mech.E., late Lecturer in Engineering at Sheffield University, for his skill and interest in registering the lathe test data.

Finally, they thank Mr. J. Harrison, Engineer to the Faculty of Metallurgy, for his unfailing care in hardening the turning tools, preparing the analytical drillings, carbide test-bars, and micro-sections, and in accurately preserving their identity throughout the research.

APPENDIX I.

Analysis of the Carbide Residues.—The residues, after being collected, washed, and dried, as described in previous papers (already quoted), were analysed as follows :—*Carbon* was determined in a separate portion by combustion in a current of oxygen. The remaining portion was ignited at dull redness to constant weight, and the residue fused thoroughly with a mixture of carbonate and peroxide of sodium. The " melt " was extracted with water, filtered, and washed. The ferric oxide resulting from the ignition of the residue was dissolved in acid, the *iron* reduced and determined volumetrically.

The filtrate was made up to a definite volume and then divided into two parts. *Chromium* was determined volumetrically in one part, after acidifying with sulphuric acid, by means of ferrous ammonium sulphate and standard potassium permanganate solutions, the latter being added until a pink colour, persisting for two minutes in the cold solution, was obtained. In the cases of the residues containing vanadium, the titrated solution was again reduced with ferrous solution, the excess of which was determined by titration with permanganate until a drop of the solution failed to yield a blue colour immediately on mixing with potassium ferricyanide solution. This second titration determines *vanadium* : the determinations were confirmed by another method (*vide infra*).

The other portion of the filtrate was made faintly but distinctly acid with hydrochloric acid, the chromic acid reduced with sulphurous acid, the solution boiled for two minutes and then cooled. A solution of potassium permanganate was next added until the vanadium was fully oxidised, then an excess of lead acetate and ammonium acetate, and the mixture allowed to digest for two hours. The precipitate was collected, washed, and ignited at a low red heat. The residue was dissolved in concentrated hydrochloric acid, the solution evaporated almost to dryness, and the residue boiled with dilute hydrochloric acid (1 acid, 4 water). The residue of tungstic oxide was collected, washed, &c., and the *tungsten* calculated.

The filtrate from the tungstic oxide was treated as follows for the determination of molybdenum and vanadium, when present.

(i.) *Vanadium Absent.*—The solution was treated with dilute ammonium hydrate until turbid, the turbidity was cleared with a few drops of acid, the solution heated to boiling, and an excess of ammonium acetate added. The precipitated lead molybdate was collected, and the *molybdenum* thus determined. Molybdenum was also determined as follows:

(ii.) *Vanadium Present.*—The solution was evaporated after adding a few cubic centimetres of concentrated sulphuric acid until copious fumes of sulphur trioxide were evolved. After diluting with water, the lead sulphate was filtered out and washed. The filtrate was treated with sulphurous acid, the excess of the latter expelled by boiling, and the *vanadium* determined by titration with standard permanganate. The titrated solution was passed through a Jones' reductor and the solution again titrated, the *molybdenum and vanadium* contents thus being obtained. The two titrations sufficed for the determination of *molybdenum* by difference.

The carbide residues were not analysed for phosphorus, sulphur, silicon, nor manganese.

APPENDIX II.

Method for the Algebraic Determinations of Constitutional Formulæ from Atomic Ratios calculated from the Analyses of the Electrolytic Residues containing mixed Carbides and Tungstide of Iron.

Method 1.—For an example select the electrolytic residue yielded by steel No. 1579, the analysis of which is given in Table I., p. 409. From this analysis, by the usual simple calculations, determine the atomic ratios of the elements present, viz. C 0·211, Fe 0·539, Cr 0·134, W 0·328 (Table V.). Then the previous researches of Arnold and Read have shown that the carbides, &c., are Fe_3C, WC, Fe_2W, and either Cr_4C, Cr_3C_2, or a mixture thereof. By the simple but tedious method of "trial," ascertain the fact that there is insufficient carbon present to form Cr_3C_2 (13·3 per cent. carbon), and that therefore the carbide present must be Cr_4C (5·4 per cent. carbon). Ascertain the carbon required for this formula, viz. $\frac{0{\cdot}134}{4} = 0{\cdot}0335$; ∴ remaining available carbon $= 0{\cdot}1775$ atom.

Let $x =$ number of atoms required by W to form WC, then C left $= 0{\cdot}1775 - x$ atoms; ∴ $Fe_3C = 0{\cdot}1775 - x$ molecules.
Therefore Fe left to form $Fe_2W = (0{\cdot}328 - x)$.
Therefore $2(0{\cdot}328 - x) = 0{\cdot}539 - 3\ (0{\cdot}1775 - x)$ or $5x = 0{\cdot}65$, and $x = 0{\cdot}13$.

Hence molecular proportions of Cr_4C, WC, Fe_2W, and Fe_3C are $0{\cdot}0335\ Cr_4C + 0{\cdot}13\ WC + 0{\cdot}198\ Fe_2W + 0{\cdot}0475\ Fe_3C$, which are equivalent to $2{\cdot}05Cr_4C + 8WC + 12{\cdot}2Fe_2W + 3Fe_3C$, which, within the limits of errors of analysis, gives the molecular constitution as $3Fe_3C + 2Cr_4C + 8WC + 12Fe_2W$.

Method 2.—*Steel No.* 1579. Atomic ratios, C 0·211, Fe 0·539, Cr 0·134, W 0·328. Compounds present Fe_3C, Fe_2W, WC, Cr_4C. As chromium all exists as Cr_4C, then Cr 134 will take C 33·5, giving 33·5 molecules of Cr_4C. Thus are left C 178, Fe 539, W 328.

Let $x =$ number of molecules of Fe_3C,
y „ „ „ Fe_2W,
z „ „ „ WC;
Then atoms of iron $= 3x + 2y$,
„ „ tungsten $= y + z$,
„ „ carbon $= x + z$.
That is to say, $3x + 2y = 539$,
„ „ $y + z = 328$,
„ „ $x + z = 178$.
On solving it will be found that
$x = 48,\ y = 198,\ z = 130$.

Hence formula must be $48Fe_3C + 198Fe_2W + 130WC + 33Cr_4C$.
Divisor for simplification = 16.

Hence within the limits of experimental error, the constitutional formulæ of the constituents of the electrolytic residue from steel No. 1579 $= 3Fe_3C + 2Cr_4C + 8WC + 12Fe_2W$, as in Method 1.

APPENDIX III.

A.

Percentage Compositions of the various Carbides, Pearlites, and Hardenites, together with their Formulæ and abrasive Hardnesses on Möh's Mineral Scale so far as they have been definitely or approximately determined.

Names of Carbides.	Formulæ.	Carbon per Cent.	Metal per Cent.	Hardness Number on Möh's Mineral Scale. (Diamond—Hardest Substance known = 10.)
Iron . . .	Fe_3C	6·$\dot{6}$	93·$\dot{3}$	6·5 (felspar—quartz)
Chromic . .	Cr_3C_2	13·$\dot{3}$	86·$\dot{6}$	8·0 (topaz)
Chromous . .	Cr_4C	5·44	94·56	7·0 (quartz)
Tungsten . .	WC	6·12	93·88	7·5 (quartz—topaz)
Vanadium . .	V_4C_3	15·00	85·00	8·5 (topaz—corundum)
Ferro-molybdenum	Fe_3Mo_3C	2·56	Fe 35·90 Mo 61·54	7·5 (quartz—topaz)

Notes.—Tungstide of iron, Fe_2W, contains Fe 37·8 and W 62·2 per cent. Abrasive hardness about 6·5 (felspar—quartz).

Commercially pure iron (99·8 per cent.) has a Möh's hardness of about 4 to 5 (fluorspar—apatite) according to its thermal treatment.

B.

Empirical Formulæ of the Pearlites and Hardenites of the Four True Steels (at present known), with Temperature Transformation Ranges (see footnotes).

Name of True Steel.	Pearlite Mixture Formula.	Hardenite (Solid Solution Formula).	Abrasive Hardness on Möh's Scale.
Iron . . .	$(21Fe + Fe_3C)$ [1]	(Fe_{24}, C)	7 (quartz)
Vanadium . .	$(72Fe + V_4C_3)$ [2]	(Fe_{72}, V_4C_3)	9 (corundum)
Tungsten . .	$(26Fe + WC)$ [3]	(Fe_{26}, WC)	7·5 (quartz—topaz).
Ferro-molybdenum	$(24Fe + Fe_3Mo_3C)$[4]	(Fe_{24}, Fe_3Mo_3C)	7·5 (quartz—topaz)

[1] Transformation range to its hardenite, 728° to 730° C.
[2] Transformation range abrupt at about 1400° C.
[3] Transformation range about 850° to 1100° C.
[4] Transformation range about 925° to 1100° C.

APPENDIX IV.

Experiments made to Determine the Relative Affinities for Carbon of the Alloying Elements of High-speed Steels.

A steel containing about 1·1 per cent. of carbon and 3 per cent. each of the alloying elements tungsten, chromium, vanadium, and molybdenum, was made, annealed, and electrolysed in the usual way. On chemical analysis the washed and dried residue was found to contain of the total:

	Per Cent.
Chromium	14·1
Tungsten	68·3
Molybdenum	73·2
Vanadium	98·7
Carbon	84·4

The proportions of the elements above mentioned would doubtless exist as Cr_4C, WC, $Mo_3{\cdot}5C$, and V_4C_3.

Iron as Fe_3C seemed to be totally absent, there being barely enough iron (about 9 per cent.) in the residue to satisfy the formula Fe_3Mo_3C.

APPENDIX V.

Brinell and Scleroscope Hardness Values of the One-ton Testing Shaft obtained from Transverse Slices cut from each End of the Bar.

Brinell Tests.

Driving headstock end	255 to 269	Mean 255
Loose „ „	241 to 255	

Scleroscope Tests.

Driving headstock end	31 to 36	Mean 33
Loose „ „	30 to 34	

The authors here feel induced to call attention to the most excellent manner in which the printers, acting upon instructions from Mr. G. C. Lloyd, the Secretary of the Institute, have reproduced the five illustrations accompanying this paper.

NOTE ON SURFACE TENSION EFFECTS IN HIGH-SPEED STEELS.

BY F. C. THOMPSON, D.MET., B.SC.
(ASSISTANT LECTURER IN METALLURGY OF THE UNIVERSITY OF SHEFFIELD).

IN the *Journal of the Iron and Steel Institute*, 1916, No. I. p. 102, in a paper entitled "Note on the Relations between the Cutting Efficiencies of Tool Steels and their Brinell or Scleroscope Hardnesses," Professor Arnold showed the lack of correlation between the Brinell and scleroscope hardnesses of plain carbon and high-speed turning tool steels and their lathe efficiencies. He attributed the enormous cutting superiority of high-speed steels of relatively low Brinell hardness value (compared with the hardness registered by quenched and tempered plain carbon steel) mainly to the remarkable "thermal stability" of tungsten hardenite over that of iron hardenite. The latter, it was pointed out, becomes soft by its almost complete reversion to troostitic iron pearlite at a blue heat (say 300° C.), whereas tungsten hardenite is capable of cutting at a red heat (say 650° C.), before transforming to relatively soft tungsten pearlite. The following suggestion is now put forward in explanation of thermal stability, based on surface tension effects, clear evidence of which was obtained from the twelve microsections described in Dr. Arnold and Mr. Ibbotson's foregoing paper, which correlates the molecular constitutions and lathe efficiencies of high-speed steels.

The carbide occurred in all cases in globular masses, the rounding of which is due to the action of surface forces. In steel No. 1574, in the annealed condition, traces of a cell-wall structure were still to be seen, which had broken up under the action of the annealing. Such a tendency for thin films or cell walls to break up and become a series of globules is quite in accord with the known effect of surface action in other media. At the highest powers of microscopic vision the sorbitic pearlite can be seen to consist of almost perfectly spherical "droplets" of a carbide embedded in a matrix of "ferrite," either *per se* or with other metals in solid solution. The sphere is the solid body which possesses the minimum surface for a given volume, and is the form taken up by a body free from other forces under the action of surface tension.

The effect of surface forces in delaying the formation of minutest globules of carbide from the solid solution hardenite, *i.e.*, the letting down of the steel, may be supposed to act in the following manner. As is now well known the solubility of a solid is dependent to some extent on the size of the particles, and especially when these become very small indeed the tendency to pass into solution is greatly enhanced. This effect is evidence of the importance of surface phenomena. On the other hand, when small particles of a solid are about to separate out from a solution, the "resistance" to the separation, due still to the action of surface forces, is great and may totally prevent crystallisation from a supersaturated solution. The higher the value of the surface tension, the greater will this inhibition be. It is here that the effect of nuclei on which the crystals can form makes its appearance. The nucleus has already a surface great compared with that of the minimum portion of crystalline matter, and hence the exercise of the greatest forces is not in operation. In this connection it may be remarked that the separation of matrix from a plain steel on tempering is facilitated by the inclusions of sulphide, and the absence of these on high-speed steels[1] would tend, though possibly only to a small extent, to hinder the decomposition of the hardenite, *i.e.*, to raise the thermal stability of the material. It is in connection, however, with the values of the surface forces themselves that the increase in stability of the hardenite of a high-speed steel is probably mainly due. The addition of one metal to another may either raise or lower the surface tension. In connection with such alloys as the special steels no definite experimental data is yet available, but if we assume that in a high-speed steel the effect of the addition of the special elements is to raise the value of the surface forces, then their remarkable thermal stability is explained. The question resolves itself at once merely into a profound refusal to allow the initial stages of letting down to set in, *i.e.*, to allow the first minute particles of carbide in the "troostitic pearlite" to form. As the temperature of the steel is raised the surface tension becomes less, with the result that the separation of the carbide from solution is no longer totally prevented, and hence "letting down" commences. Once these first small masses of carbide have formed the rest of the process is rapidly accomplished, since each particle acting as a nucleus renders the further precipitation more easy and complete.

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[1] This was proved by Arnold in a research on "The Influence of Cobalt on High-speed Steel," presented to the High-speed Steel Association in 1914.

CORRESPONDENCE.

Dr. J. H. **Andrew** and Mr. G. W. **Green** wrote that whilst admiring the careful and interesting carbide determinations of the authors they disagreed with them upon their absorption and recalescence curves and their interpretation.

In the first place the two lower points in the heating curve were 37° higher than similar points obtained independently by Yatsevitch and the writers, whilst their magnitude was likewise reversed; moreover, it was inconceivable that the tungsten-pearlite should be transformed to tungsten-hardenite in a series of jumps: a rather unusual manner for a physico-chemical reaction to take place.

The lower point occurring in the heating curve of that steel at 775° C. was similar to that invariably found in chromium steels at a temperature just below the main absorption point. That, in conjunction with evidence furnished by the Brinell hardness curve of quenched specimens which showed no change in the hardness produced by quenching from just above the 775° point, did not support the authors' contention that it was due to the transformation of chromium pearlite into chromium hardenite. The increase in hardness found both by Yatsevitch and the writers by quenching from just above the 850° point suggested that that, and not the lower point, was concerned with the carbide transformation.

The hardness curves obtained by Yatsevitch and the writers, by quenching at different temperatures upon heating, were shown in Figs. A and B, where the great increase in hardness above the 850° C. point and ineffectiveness of quenching at any temperature below that point, was clearly revealed.

With regard to the higher point, namely 1067° C., if that were a carbide change a material increase in hardness would be expected in a specimen quenched above, to one which was quenched just below. The writers had found, however, that the hardness was practically a linear function of the temperature over the range 850° C. to 1300° C., due, it would seem, to the gradual solution of the excess carbide.

Consideration of the writers' experimental evidence pointed to the fact that that point was due to the solution of a substance other than carbide, possibly tungstide of iron, which, by going into solution and acting thereby as a dilutant, would rather tend to bring down the hardness. That, however, was compensated for by the gradual increase in solution of free carbide with rising temperature.

The writers had shown elsewhere that in cooling tool steel of the composition in question, two recalescence points were possible. One occurred at about 740° C., which was obtained by cooling slowly from below 950° C., after which cooling the steel was as soft as in the annealed condition, thereby showing that the point was the reversal of the 850° C. point on heating and due to the complete break-down of the solid solution. Yatsevitch came to the same conclusion. Consequently for efficient hardening that point must be suppressed.

By cooling from a higher temperature the lower point similar to that of the authors was obtained. The raising of the initial temperature caused a gradual suppression (not depression) of the higher point with a corresponding increase in the lower point.

A similar case had been investigated by Dejean, following upon Benedicks' work, and confirmed by Portevin. The general view taken by those workers was that the upper point was the austenite-troostite transformation, and the lower point the austenite-martensite transformation, in which the martensite consisted of a solution of carbides in alpha iron. The point might be due, therefore, to the change from gamma to alpha iron without precipitation of the carbide.

Professor E. D. **Campbell** (Michigan University, Ann Arbor) wrote that few papers had been published dealing with the correlations existing between the chemical constitution of high-speed tool steels and some of their physical properties, in which the experiments carried out had shown such painstaking care as that of the authors. It was on data such as were given in Tables I., II., III., and VII. that metallurgists depended for guidance on the complex problems of chemical constitution of steel and its correlation with physical properties.

The data in Tables IV. and V. were computed from figures given in previous tables and, while very useful for purposes of further computations, depended only upon a knowledge of the atomic weights of the elements involved.

The theoretical formulæ given in Table VI. might be open to question by chemists who had paid much attention to the development of physical chemistry during recent years and especially to the formation of mixed crystals or solid solutions. According to the method used for calculating those formulæ, as given in detail in Appendix II., the fundamental assumption was made that the whole of the chromium found in the carbide residues existed as a pure chromium carbide, Cr_4C. All the theoretical formulæ obtained by " trial " or by algebraic calculations, necessarily rested upon the fundamental premise that all the chromium in the carbide residues existed as a pure carbide of chromium, with the empirical formula Cr_4C. Those interested in the attempt to get at the true chemical constitution of the complex carbides found in steel might very properly inquire whether there was any experimental evidence to prove the truth of the fundamental assumption on which those calculations depended.

According to the results reported by Arnold and Read[1] in their valuable paper on "The Chemical and Mechanical Relations of Iron, Chromium and Carbon" if the percentage of chromium was very low

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[1] *Journal of the Iron and Steel Institute*, 1911, 1, p. 257.

PLATE XXVA.

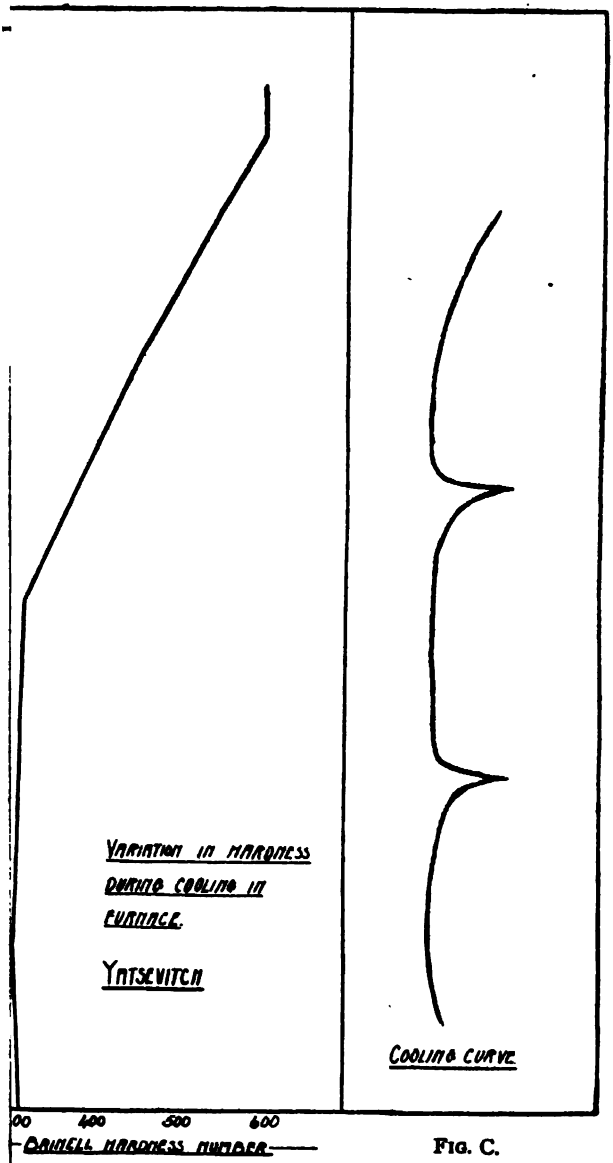

FIG. C.

To face p. 432.

(under one per cent.), none of the carbon existing as a carbide of chromium was present as the Cr_4C carbide. When the chromium in the steel was 4·97 per cent. only one-seventh of the carbon found combined with chromium was in the form of the Cr_4C carbide, while with over 10 per cent. of chromium only one-third of the carbon existed as carbide of chromium in the form Cr_4C. It was not until chromium had reached 15 per cent. or more that the only carbide of chromium reported was that having the formula Cr_4C.

In all the high-speed steels under discussion the chromium was under 3 per cent., so that it would be interesting to inquire upon what, if any, experimental evidence the authors of the calculations based their fundamental premise.

Mr. J. **Ferdinand Kayser** (Spartan Steel Co., Ltd., Research Department, Sheffield) wrote that he was much surprised at the authors putting forward absorption curve, 3rd heating, Fig. 1, as typical of the heating curves given by such steels as they had examined. He did not doubt the accuracy of the authors' work, but he suggested that the initial conditions before obtaining the curve published had been of a rather exceptional nature. The nature of the heating curve of those steels depended upon initial condition, and three of the very important factors which determined initial condition were: (1) Highest temperature reached during previous treatment; (2) rate of cooling during previous treatment; and (3) lowest temperature attained before determination of next heating curve. For example, curve 1, Fig. A, showed the differential heating curve obtained with a specimen of steel of the following analysis:

C.	Mn.	Si.	Cr.	W.	V.	Mo.
0·67	0·09	0·03	3·96	17·72	0·25	0·54

Curve 2, Fig. A, showed the heating curve obtained with the same specimen after heating to 1050° C., cooling quickly to 380° C., then again determining the heating curve. He found that all the high-speed alloy steels which he had examined, which included Fe-C-Cr, Fe-C-Cr-Mo, and Fe-C-Cr-W alloys, both with and without vanadium, gave heating curves which were very easily altered by the variation in any of the three factors just mentioned. He would ask the authors what exactly were the previous treatments? What were the highest temperatures obtained, the rates of cooling from those temperatures, and the lowest temperatures reached before determining the next heating curve? The recalescence curve also was very misleading, and could not very well be described as a typical cooling curve of the alloy under investigation; it was no doubt typical of that particular alloy when heated to that particular temperature and cooled at some (unrecorded) velocity. It had to be remembered, however, that in all such alloy steels the position and also the number of recalescence points depended upon initial temperature and cooling velocity. What evidence had the authors in their possession to lead them to assume that the low point at 408° C. corresponded with the change of the mixed hardenites of iron and chromium to their mixed pearlites ?

Referring to the results on the lathe, he (Mr. Kayser) thought too little stress was laid upon the results obtained, which clearly demonstrated the very superior cutting qualities of a tungstenless steel. The authors mentioned that they had again experienced the erratic behaviour of molybdenum. Considering that they had apparently made only one ingot to each analysis he could not agree that they were in a position to say whether the alloys were erratic in their behaviour or not. For the last two years he had been experimenting with Cr-Mo-V-C steels, and he had never experienced any difficulty in getting results from tools cut from one bar, which, so far as constancy went, compared quite favourably with ordinary tungsten high-speed steel results, but he found that the erratic behaviour of one cast compared to another was so great as to eliminate the alloys from the commercial market. The addition of substantial percentages of cobalt, however, he (Mr. Kayser) had found acted as a complete stabiliser and also improved the cutting efficiency in a remarkable manner. By such means molybdenum high-speed steels, which had for so long to be kept inside the laboratory, could now be marketed as super high-speed steels.

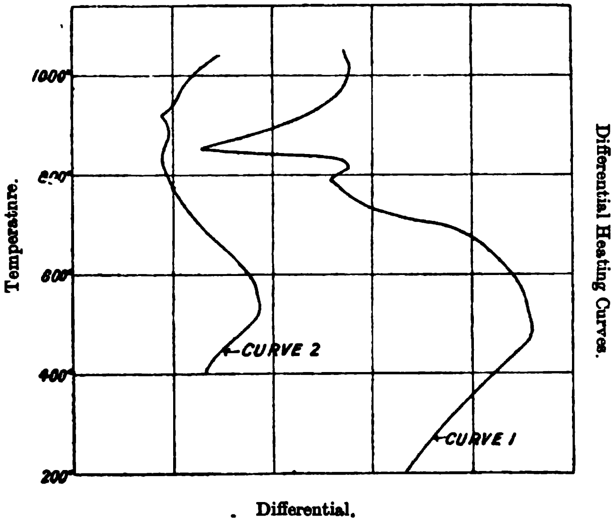

Fig. A.

Referring to Dr. Thompson's remarks, he wished to ask him to define the term "thermal stability." Dr. Thompson was of course aware of the fact that what was commonly called "18 per cent. H.S." was improved by reheating to say 600° C. and then cooling, and also that the length of time at 600° C. had no effect upon the durability of the tool. His (Mr. Kayser's) experiments had shown that the cutting efficiency of such a tool was almost nil if put to work at the maximum reheating temperature instead of being allowed to cool down. Probably that very important result would suggest its own explanation to Dr. Thompson.

THE CARBURISATION OF IRON AT LOW TEMPERATURES.

By ANDREW McCANCE, D.Sc., A.R.S.M. (Glasgow).

The interest which has been taken in this question since the publication of Byrom's paper, "Note on the Carburisation of Iron at Low Temperatures in Blast-Furnace Gases,"[1] has been due in no small measure to the unexpectedness of the results there put forward for the first time, and the confirmation of these results by Stead. With the object of elucidating the theory of the actions taking place, Carpenter and Smith[2] have published an extensive research on the action of pure CO on electrolytic iron, but their results only emphasise the complexity of the interactions without explaining them.

The object of this short note is to show how an insight into the reactions taking place can be obtained from the consideration of the variation of the equilibrium conditions with temperature. In each case the composition of the gases has been calculated, but the figures have been checked by experimental results where these are available.

To begin with, pure CO tends to decompose according to the reaction

$$2CO = C + CO_2 \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the composition of the mixed gases at any temperature can be ascertained by passing CO_2 over carbon. The reverse reaction, however, is very difficult to bring about without the use of catalysts. Iron is one of these catalysts, and when pure CO is passed over iron decomposition starts with the deposition of carbon. The action is a surface action—it is only the gas in contact with the iron which is decomposed, but convection and circulation cause this decomposed gas to be replaced by fresh gas, and so the average content of CO_2 in the total volume gradually increases. It rises slowly, however, as the following results of Carpenter and Smith show :

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[1] *Journal of the Iron and Steel Institute*, 1915, No. II. p. 106.
[2] *Ibid.*, 1918, No. II. p. 139.

Time (Hours).	Per Cent. CO_2.
0	0
113	20·27
138	36·67
168	38·67
235	41·07

The composition of the gas at atmospheric pressure in equilibrium with carbon can be ascertained by means of the equation given by Carpenter and Smith and slightly modified for convenience, where x is the proportion of CO

$$\log \frac{x^2}{1-x} = 7·71 - \frac{8290}{T} + ·0007\,T$$

and curve 1, Fig. 1, gives graphically the percentage of CO_2 plotted against temperature. At 650° C. it will be seen that the composition of the gas is 61·5 CO_2 and 38·5 CO, giving a ratio $\frac{CO_2}{CO}$ of 1·60. Pure CO in contact with iron will be decomposed until the mixed gases have this composition at this temperature, and it is interesting to note that the composition of the gas which was drawn off last in Experiment IX. of Carpenter and Smith was

CO	45·23
CO_2	45·78
H	5·70
N	2·83

which shows how the gas is gradually approaching the equilibrium ratio.

As the gas in contact with the iron undergoes this slow enrichment with CO_2 at different times, depending on the amount of CO_2 present, other reactions are possible and will take place within the limits of composition assigned to them. By drawing a diagram of the CO_2 percentage and the temperature for each reaction the chemical changes taking place can be very readily seen. This diagram is given in Fig. 1. Curve 1, as already explained, gives the compositions for equation (1).

The next reaction which can be considered is the formation of cementite—

$$3Fe + 2CO = Fe_3C + CO_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and using the same symbols as before, the equilibrium constant is

$$K = \frac{1-x}{x^2.P}$$

Schenk gives the value of $\frac{1}{K}$ at 650° as 31,600, measuring P in millimetres, and this has been used to calculate the composition at any temperature from the equation—

$$\frac{d}{dt}\cdot\log K = -\frac{Q}{RT^2}$$

where Q is the heat of reaction. The results for equation (2) are given by curve 2, and they show that at 650° C. a gas containing 2·3 per cent. CO_2 is in equilibrium with cementite and iron. The proportion increases rapidly as the temperature is lowered, and at 575° C. it is roughly 19 per cent. If less

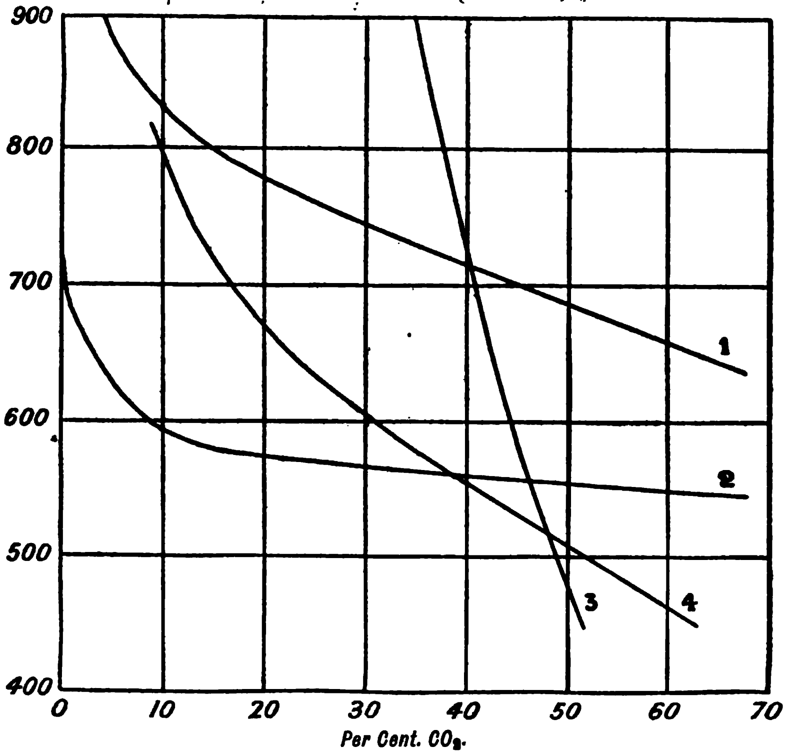

Fig. 1.

Curve 1.—$2CO = CO_2 + C$.
„ 2.—$3Fe + 2CO = Fe_3C + CO_2$.
Curve 3.—$Fe + CO_2 = FeO + CO$.
„ 4.—$3FeO + 5CO_2 = Fe_3C + 4CO_2$.

than the equilibrium percentage be present at any temperature, then cementite will be formed, while if more, cementite already formed will be reduced again. The percentage varies with the pressure as well, and when less than atmospheric the percentage is also reduced. Under normal conditions it will only be in the very early stages of the process that cementite can be formed from iron direct through the action of pure CO.

As the CO_2 content increases a stage is reached when the iron is oxidised by the mixed gases according to the reaction—

$$Fe + CO_2 = FeO + CO \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

which is independent of the pressure. This reaction has been worked out by Baur and Glassner,[1] but their results at high temperatures do not agree with one another. At lower temperatures, however, they agree with the calculated values, and using these values, curve 3 has been drawn, and from this it will be seen that at 650°, if the gases contain more than 42 per cent. CO_2, then the iron will be oxidised to FeO.

Near the surface of a piece of solid iron in pure CO the CO_2 percentage will rise rapidly owing to reaction (1), and the CO_2 will then diffuse away into the surrounding gas, but if the percentage gets over that required by equation (3) before it diffuses, then ferrous oxide will be formed, and this in spite of the fact that the average composition is below the requisite amount.

Ferrous oxide can be converted directly into cementite by the action of CO, however,

$$3FeO + 5CO = Fe_3C + 4CO_2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and the composition curve for the mixed gases has been drawn in curve 4 from the results of Schenk, Semiller, and Falke.[2]

The striking result shown by this curve is that above 550° C. ferrous oxide is more easily converted into carbide than pure iron. At 650°, for instance, pure iron can only be converted into cementite when less than 2·3 per cent. of CO_2 is present in the CO, whereas ferrous oxide can be converted up to 23 per cent. CO_2. Under normal conditions, when the iron will be exposed to the action of air in the gases to which it is exposed, the limits for the formation of cementite will be the limits in the composition of the gases for reaction (4).

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[1] *Zeit. physic. Chem.*, 1903, 43, p. 354.
[2] *Berichte*, 1906, p. 1704.

In the experiments of Carpenter and Smith the iron was always pitted as if by oxidation, while in many cases oxide was directly observed, but owing to the fact that the gases in contact with the iron could have any proportion of CO_2 up to 61·5, the limit of CO_2 in reaction (1), it is impossible to decide from their experiments what is the upper limit for the production of cementite of CO_2 in the mixed gases. Under the conditions of their experiments the only way to determine this would be to start with a definite mixture of CO_2 and CO and to find the highest content of CO_2 which would form cementite, and the lowest content which would not. The mean of these values would give the approximate equilibrium value. The underlying assumption, which they themselves would probably admit, is, of course, that substance *x* which they found in the iron is cementite.

In blast-furnace gas the presence of free air assures the presence of ferrous oxide, while the nitrogen lowers the partial pressure of the carbon gases. Thus, although the equilibrium value of CO_2 for reaction (4) is 23 per cent. under atmospheric pressure, when the gases are diluted with 55 per cent. nitrogen the value is reduced to 20 per cent. In the original report of Byrom, the blast-furnace gas had a $\frac{CO_2}{CO + CO_2}$ ratio of from 18 to 17 per cent., which is well under the equilibrium value. Such gases would therefore be expected to carburise iron at any temperature below about 660° C., while below about 500° C. the rate at which the actions take place would be so low that no appreciable effect could be observed.

It may be stated in passing that the curve given in Fig. 1 can be easily extended to higher temperatures so as to include the case-hardening of steel, though they are somewhat altered, of course, by the fact that the cementite is in solution in the iron.

CORRESPONDENCE.

Professor H. C. H. Carpenter, F.R.S., and Mr. C. Coldron Smith, M.Sc., wrote that the subject Dr. McCance had brought before the Institute was of great interest, and its continued study could not but ultimately prove of practical value in the iron and steel industry.

The author had referred frequently to the recent paper[1] by the writers on the subject. They regretted, therefore, that he appeared to have misunderstood the primary object of their experiments, which was essentially to investigate and if possible to isolate the solid phase or phases that were produced by the reaction between carbon monoxide and pure electrolytic iron below the A1 inversion. In such an investigation the reactions that took place, and in particular any theory that provided an insight into those reactions, could not fail to interest and be of great assistance to researchers in that field of knowledge.

In his interesting endeavour to elucidate the complexity of the reactions between iron and carbon monoxide, it would have been well if Dr. McCance had seen fit to dwell upon some of the difficulties of the problem. He stated on p. 437 that in "the reaction $2CO = C + CO_2$ the composition of the mixed gases at any temperature can be ascertained by passing CO_2 over carbon." That assertion in that somewhat bald form was misleading, since while it was theoretically true, it was doubtful whether it had been achieved in practice.

As justifying that statement it might be pointed out that Rhead and Wheeler[2] were not able to determine the composition of the gases in equilibrium with carbon below a temperature of 850° C., since equilibrium could not be obtained within a reasonable period of time. In a series of experiments made on the reduction of carbon dioxide by wood charcoal they were unable to obtain a disappearance of more than 0·7 per cent. of this gas after 122 hours' heating at 700° C. On the other hand, O. Boudouard,[3] using quite another method, claims to have obtained the "correct" (as calculated from the Rhead and Wheeler equation) equilibrium percentage of carbon dioxide after heating that gas for twelve hours at 650° C. in contact with wood charcoal. The statement of those discrepancies was merely intended to put the problem in a proper perspective and to emphasise the difficulties of interpreting the experimental evidence available.

In speaking of the reaction which occurred by passing "pure" carbon monoxide over iron it was difficult to understand why Dr. McCance had chosen for illustration (p. 438) one of the writers' experiments in which a composite gas was employed, and the writers would like to inquire how the figures he gave for the percentage of carbon dioxide were obtained from their results.

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[1] *Journal of the Iron and Steel Institute*, 1918, No. II. p. 139.
[2] *Transactions of the Chemical Society*, 1910, vol. 97, p. 2188.
[3] *Ann. Chem. Phys.*, 1910 [vii.], xxiv. 5.

Exception must be taken to the statement on p. 438 that "pure CO in contact with iron will be decomposed until the mixed gases have this composition (viz. 61·5 per cent. CO_2) at this temperature (viz. 650° C.)." That could only be true so long as the iron acted catalytically, for as soon as other solid phases, like FeO, made their appearance, the amount of carbon dioxide in equilibrium with all the phases present was likely to diminish. Moreover the solid phases produced were deposited on the iron and so prevented access of the gas, thereby checking the catalytic effect and hence retarding the establishment of an equilibrium which (assuming it to take place without modification by other phases) was very slow of attainment. Where other metals were used that merely function as catalysts, *e.g.* cobalt, the equilibrium $2CO \rightarrow CO_2 + C$ appeared to be fairly readily attained.[1] O. Boudouard found that carbon monoxide in the presence of cobalt at a temperature of 650° C. yielded 61 per cent. CO_2 after seven hours' heating. A further possibility had also to be considered. With the production of carbon dioxide by the dissociation of carbon monoxide, oxidation of the iron might set in and remove the dioxide almost as rapidly as it was formed (until the final pressure was only a fraction of the initial pressure), and that might not necessarily correspond to any equilibrium value.

The writers regretted that Dr. McCance discussed so briefly the application of the van't Hoff equation to the equilibrium $3Fe + 2CO \rightleftarrows Fe_3C + CO_2$. They were anxious to know if the heat of formation of the triferrous carbide or the above heat of reaction had been determined with sufficient accuracy to warrant its use quantitatively or even qualitatively. It must also be borne in mind that the value of the equilibrium constant (K) had not been determined directly. In addition the author had not pointed out in applying the "principle of mobile equilibrium" whether the reaction under discussion was to be taken as being carried out at constant volume or at constant pressure. Both problems ought to be considered, as the writers' experiments showed what great differences were obtained in the two cases. In fact they were of the opinion that the present state of knowledge relating to the problem under discussion was not sufficient to enable any certain prediction to be made of the course that reactions between carbon monoxide and iron would take. As an instance of that, the diagram put foward by the author did not (and it was difficult to imagine at present how any diagram could) take into consideration the amount of iron relative to the volume of the reaction vessel in which the gas undergoing decomposition was contained. Schenck and Falcke had also asserted the importance of that iron/gas volume ratio.

They (the writers) noted Dr. McCance's assumption in all his arguments that the carbide produced in the above reaction was Fe_3C.

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[1] *Ann. Chem. Phys.*, 1910 [vii.], xxiv. 5.

The composition of that carbide had not yet been determined. The writers hoped to attempt that before long. It was interesting to note that R. Schenck[1] had put forward some evidence in favour of the formulæ Fe_7C or Fe_6C for the carbide produced below the A1 inversion, and he quoted in support the analogous manganese carbide (Mn_6C or Mn_7C). He emphasised also the desirability of isolating the carbide for the purpose of analysis.

On p. 440 Dr. McCance (in agreement with Schenck) drew the inference from his diagram that ferrous oxide was more easily converted into carbide than pure iron at a temperature of 650° C. There was strong support in favour of that, and it was unfortunate that ferrous oxide offered such little advantage as a starting point for the isolation of the carbide by reason of the difficulties in preparing the former and in separating the latter from a powder that was likely to contain, in addition, metallic iron, carbon, and iron oxide.

Dr. McCance had made some suggestions on p. 441 for experimenting with mixtures of carbon monoxide and dioxide. Any experiments with gas mixtures would require very rigid conditions of control as so many variables were present. The results that might be obtained by the passage of those gas mixtures over iron would be difficult of interpretation, as it was possible to have the gas in the reaction vessel of very variable composition according to its position, for example, that in the immediate neighbourhood of the iron could be and usually was different in composition from that in a more remote part of the vessel.

Mr. J. E. Fletcher (Dudley) wrote that the curve 4 in Fig. 1 was of very great interest in a number of metallurgical processes. Dr. McCance referred to the work of Schenck, Semiller, and Falcke as his authorities for bringing forward that curve. It would be of interest to learn whether any British metallurgist had checked the results. Perhaps Dr. McCance himself had confirmed them.

In the reheating of iron piles in the gas furnace the hard spots occasionally found in the rolled bars had been attributed by some to the carburising atmosphere which, under certain conditions, could contain a high percentage of carbon monoxide.

If the curve 4 in Fig. 1 was correct, then such carburising of oxidised iron was impossible at, say, 1200° C., for by extending the curve to the higher temperatures the CO content of the furnace gas would have to be at least 97 per cent., a practical impossibility in a furnace which could not be perfectly sealed.

The fact that above 550° C. ferrous oxide was more easily converted into carbide than pure iron was important, and might account for the hard surface patches which occurred in iron sheets whose surfaces were more or less oxidised when charged into gas furnaces wherein the working temperatures were in the neighbourhood of 700° C. and the gases used were of a reducing character. Such hardness in both bars and plates rolled from piled iron had been difficult to explain. Previously it had been usual to associate the presence of surface oxide with softening rather than with hardening. Dr. McCance had again done the Institute good service by bringing forward theoretical explanations, deduced from experimental evidence, for phenomena met with in works practice and otherwise inexplicable. The graphs of the equilibria of the possible carburising reactions would be found of great value in such cases as concerned the heating of iron and mild steel in reducing atmospheres at comparatively low temperatures.

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[1] *Zeitschrift für Elektrochemie*, Bd. 24, Aug. 1, 1918.

A more thorough understanding of the laws of physical chemistry was becoming a necessity for the practical metallurgist of the future, and thanks were due to Dr. McCance for his endeavours to weld together the theoretical and the practical, as again evidenced in his paper.

Dr. **McCance** (Glasgow) wrote that his desire to condense his short note had perhaps led him to use language which was not altogether free from ambiguity, but he did not think that anyone would be misled by that to any extent. His note was concerned with the principles of the reactions which took place in low temperature carburising, and the manner of carrying out confirmatory experiments was in no manner considered, so that bearing that in mind he thought that the criticism of Professor Carpenter and Mr. Smith as to the difficulties of the experimental problem—difficulties which he freely admitted—hardly needed to be further discussed.

They asked, however, how the percentage of CO_2 given on page 438 was obtained from their results. It was copied from p. 179 of their paper because the reason that that experiment was used was that it was the only experiment in which the gases which came off last were separately collected and analysed. The result, it was thought, would illustrate the tendency of the CO_2 to increase in the neighbourhood of the specimen, but it was not meant to give the correct quantitative relation theoretically demanded. In a similar way the statement to which exception was taken was, he thought, sufficiently covered by the previous paragraph in which the iron was being assumed to act purely catalytically.

The curves given in Fig. 1 were all for atmospheric pressure, so that when the principle of mobile equilibrium was applied it would of course refer to constant pressure conditions.

The results of those equilibrium reactions could be checked among themselves in a very simple manner, and he (Dr. McCance) had done so, and was convinced that the curves as given were substantially correct, although they were drawn to lie evenly among the experimental points. Theoretical calculation showed also that curves (1) and (3) were accurate, and that the other curves could be deduced from those two without other experimental results. Taking every consideration into account therefore, the curves were sufficiently accurate to justify the conclusions drawn, and more accurate determinations would only alter the position of the lines to a minor extent. It would be of great interest, however, to have those relations revaluated, for the reactions were fundamental in the metallurgy of iron, and he had been drawn to the study of them through his investigations on open hearth practice.

He did not understand their reference to the "iron/gas volume ratio." Under equilibrium conditions such as he had dealt with the relative volumes of the reactants did not enter at all into the result, and he could only assume that they had in mind their own experiments in which the conditions precluded any attempt at equilibrium, and consequently in which the relative volumes of the iron and the gas would influence the final result.

In reply to Mr. Fletcher's question it was to be regretted that no British metallurgist had checked the results of the German investigators of those reactions experimentally. There were other ways of checking them, however, amongst themselves, and when that was done it showed that in some cases there was a great need for revision. That was especially so in those reactions where solid carbon was one of the components such as FeO–C and Fe_3O_4–C.

Mr. Fletcher's remarks on hard spots in iron piles were interesting, and he (Dr. McCance) regretted that he had no experience of that trouble and so was unable to offer any opinion.

Enormous strides had been made in recent years in the extension of physical-chemical laws, and already with insufficient data the course of many reactions could be calculated with a fair degree of correctness. Time only was necessary to determine more accurate data, which would then be sufficient to predict *à priori* the exact course of many high temperature reactions without recourse to experiment.

NOTE ON THE LIQUIDUS IN THE IRON-CARBON DIAGRAM

BASED ON A DEDUCTION FROM THE EXPERIMENTS BY CARPENTER AND KEELING.

By G. CESÀRO (Liège University).

PART I.

The author has endeavoured to ascertain the course of the curve joining the points at which molten iron-carbon alloys commence to solidify, if, instead of taking as abscissæ the proportions, by weight, of carbon contained in the alloy, the abscissæ were taken as either x, the number of atoms contained in a unit of the alloy composed of 100 atoms, or as y, the number of molecules of cementite (Fe_3C) contained in a particle of the alloy composed of 100 molecules, and assuming the iron molecule to contain two atoms.

Plate XXVI. shows that the curve relating to y approaches more closely to a straight line than the curve relating to x, which, assuming Raoult's law to be applicable to the case under examination, appears to support the hypothesis that the molten iron-carbons are composed of iron + cementite and not iron + carbon. The two lines are simply plotted as follows:

The y Curve.—If c be the weight of carbon contained in a mass, 100, of the alloy, the latter will be composed, by weight, of:

Cementite . . . $15c$
Free iron . . . $100 - 15c$

The molecular composition will be obtained by dividing these weights by the molecular weights of cementite (180) and of iron (112) respectively—assuming the Fe molecule to contain two atoms. On simplifying we have:

$$\text{Molecular composition}\begin{cases}\text{Cementite} \;.\;.\;.\; \dfrac{c}{3}\\[2ex] \text{Free iron} \;.\;.\;.\; \dfrac{100-15c}{28}\end{cases}$$

so that, on a total number of $\frac{c}{3} + \frac{100-15c}{28}$ molecules the alloy will contain $\frac{c}{3}$ molecules of cementite. From this it may be concluded that the number y of cementite molecules contained in 100 molecules of the alloy is

$$y = \frac{2800\,c}{300 - 17\,c} \quad . \quad . \quad . \quad . \quad . \quad (A)$$

On taking the values of y as abscissæ and the values of T as ordinates the curve shown in Plate XXVI. is obtained.

The x Curve.—It will be found similarly on the iron-carbon hypothesis that the number x of atoms of carbon contained in a unit of 100 atoms is:

$$x = \frac{1400\,c}{300 + 11\,c} \quad . \quad . \quad . \quad . \quad . \quad (B)$$

Variation of T with c.—If the variation be assumed to be rectilinear on both hypotheses, and the line be determined by the observations made by Carpenter and Keeling,[1]

$$c = 0{\cdot}12 \qquad T = 1504^\circ$$
$$c = 4{\cdot}37 \qquad T = 1136^\circ$$

which give, respectively:—

$$x = 0{\cdot}558 \qquad y = 1{\cdot}128$$
$$x = 17{\cdot}577 \qquad y = 54{\cdot}211$$

we obtain, on the iron-carbon hypothesis,

$$T_x = 1516{\cdot}06588 - 21{\cdot}62289\,x,$$

and, on the iron-cementite hypothesis,

$$T_y = 1511{\cdot}81998 - 6{\cdot}93254\,y,$$

The latter line is that which, in the drawing, connects the point A with the point B. These formulæ will give the initial temperature of solidification in terms of c, on substituting the values (B) and (A) for x and y. It is easier, however, for the purposes of numerical calculation, to calculate, to begin with, the valency of x and of y for each value of c, and then to replace them in T_x and T_y. The following table was obtained by these means and also served to plot the two curves.[2]

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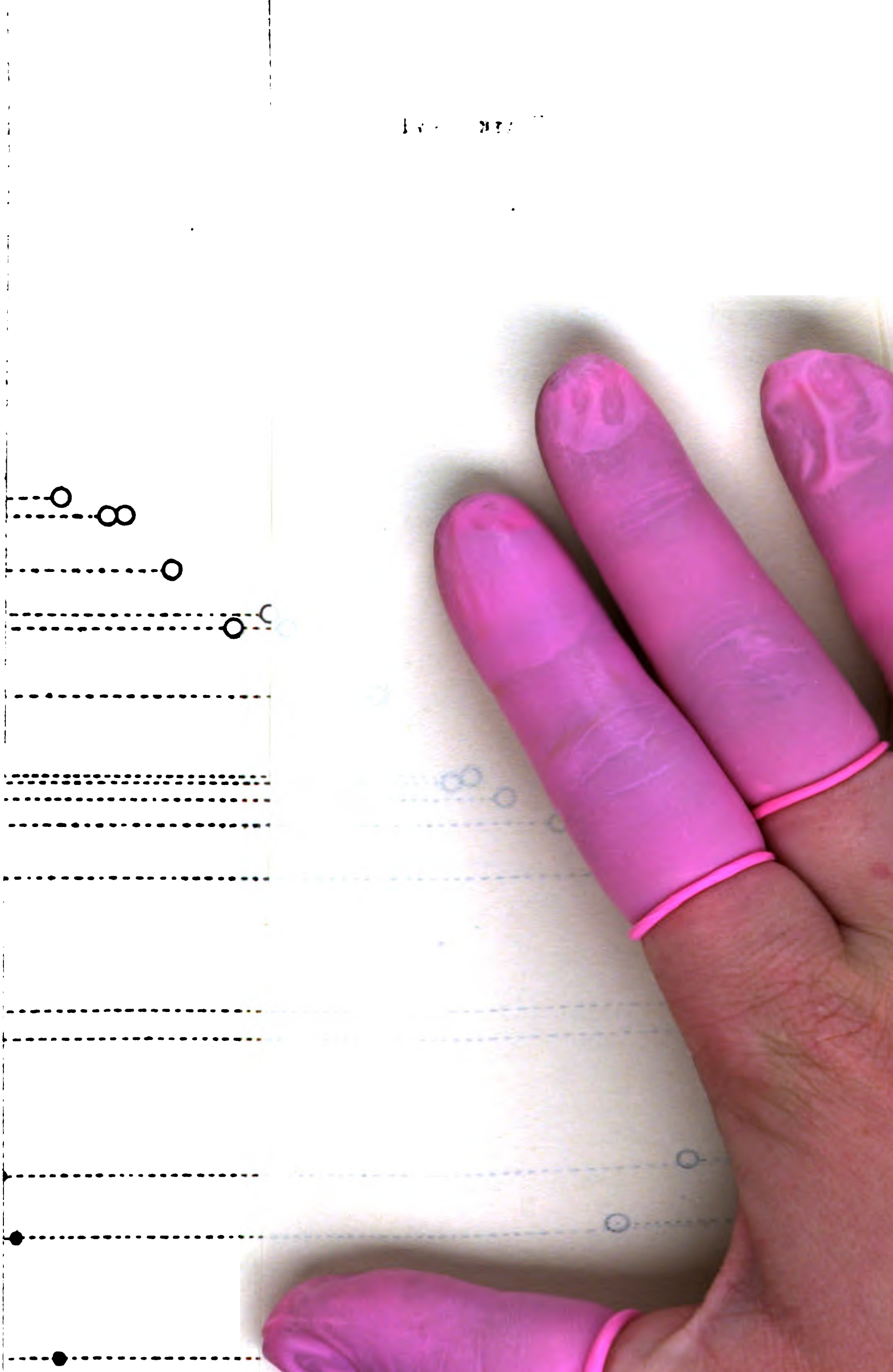
[1] *Journal of the Iron and Steel Institute*, 1904, No. I. p. 224.

[2] Between x and y the relationship is $x = \frac{50\,y}{100 + y}$ which also serves to pass from one curve to another.



emperature T at which a molten

nt of the alloy formed of 100 atoms (Cu

tained in a weight of alloy formed of

To face p. 448.

c.	*x*.	*y*.	T_x.	T_y.	$T_{mes.}$ (C.K.)	$T-T_x$.	$T-T_y$.
Per Cent.	Per Cent.	Per Cent.	Degrees.	Degrees.	Degrees.	Degrees.	Degrees.
0·12	0·558	1·128	1504	1504·0	1504	...	...
0·16	0·742	1·507	1501·4	1500·0	1498	−2·0	−3·4
0·17	0·788	1·602	1499·0	1500·7	1497	−2·0	−3·7
0·24	1·110	2·271	1492·1	1496·1	1492	−0·1	−4·1
0·38	1·749	3·625	1478·2	1486·7	1479	0·8	−7·7
0·47	2·156	4·507	1469·4	1480·6	1482	12·6	1·4
0·53	2·426	5·100	1463·6	1476·5	1473	9·4	−3·5
0·61	2·784	5·897	1455·9	1470·9	1469	13·1	−1·9
0·80	3·627	7·821	1437·6	1457·6	1457	19·4	−0·6
0·80	3·627	7·821	1437·6	1457·6	1454	16·4	−3·6
0·81	3·671	7·924	1436·7	1456·9	1460	23·3	3·1
0·93	4·197	9·163	1425·3	1448·3	1443	17·7	−5·3
1·31	5·833	13·207	1389·9	1420·3	1426	36·1	5·7
1·51	6·677	15·412	1371·7	1405·0	1406	34·3	1·0
1·69	7·426	17·444	1355·5	1390·9	1388	32·5	−2·9
1·81	7·921	18·824	1344·8	1381·3	1383	38·2	1·7
1·85	8·085	19·289	1341·2	1378·1	1383	41·8	4·9
1·97	8·574	20·697	1330·7	1368·3	1367	36·3	−1·3
2·12	9·188	22·488	1317·4	1355·9	1350	32·6	−5·9
2·21	9·540	23·580	1309·8	1348·3	1354	44·2	5·7
2·25	9·700	24·069	1306·3	1344·9	1352	45·7	7·1
2·25	9·700	24·069	1306·3	1344·9	1348	41·7	3·1
2·47	10·569	26·805	1287·5	1326·0	1330	42·5	4·0
2·63	11·194	28·846	1274·0	1311·8	1305	31·0	−6·8
2·67	11·349	29·363	1270·7	1308·2	1306	35·3	−2·2
2·74	11·619	30·274	1264·8	1301·9	1300	35·2	−1·9
2·85	12·042	31·723	1255·7	1291·9	1292	36·3	0·1
3·03	12·726	34·142	1240·9	1275·1	1277	36·1	1·9
3·29	13·701	37·743	...	...	...	...	...
3·42	14·182	39·598	1209·4	1237·3	1238	28·6	0·7
3·51	14·512	40·894	1202·3	1228·3	1230	27·7	1·7
3·87	15·816	46·266	1174·1	1191·1	1190	15·9	−1·1
3·98	16·208	47·964	1165·6	1179·3	1171	5·4	−8·3
4·37	17·577	54·211	1136	1136	1136	...	...

This table shows that the difference $T - T_y$ between the temperature as measured, and that calculated on the hypothesis $Fe_3C - Fe_2$ (assuming the variation to be rectilinear), never reaches 10°, an amount which is within the limits of experimental error. The following are the scales adopted in the curves as originally plotted :

T . . . . . . 1° = $\frac{1}{2}$ millimetre.
x . . . . . . $\frac{1}{10}$ atom of carbon in 100 atoms = $\frac{1}{2}$ millimetre.
y . . . . . . $\frac{1}{10}$ molecule of cementite in 100 molecules = $\frac{1}{2}$ millimetre.

It may be objected to the interpretation given above that Raoult's law (which leads to a straight line) cannot be applied except to :

1. Dilute solutions.
2. Alloys not forming mixed crystals on commencing to solidify.

Now, eutectic iron contains 54 per cent. of molecules of cementite, and besides, up to at least 1·8 per cent. of carbon, it deposits mixed crystals from the commencement of the solidification of ferro-carbons. In view of this difficulty the author sought to compare the two hypotheses by applying, to the figures given by Carpenter and Keeling, a more general law, expressed by the Le Chatelier-Schroeder formula :

$$lz = \frac{Q}{2}\left(\frac{1}{T_0} - \frac{1}{T}\right) \quad . \quad . \quad . \quad . \quad . \quad (C)$$

In this formula T is the absolute temperature (T° Centigrade + 273°) and z the number of molecules of the solvent (γ-iron for the branch under consideration) contained in a particle of alloy forming, altogether, a single molecule : that is to say that, taking as above, on the cementite-iron hypothesis, y as the number of molecules contained in 100 molecules of the alloy, we have :

$$z = 1 - \frac{y}{100}$$

and similarly, on the iron-carbon hypothesis :

$$z = 1 - \frac{x}{100}.$$[1]

We may also set out, as direct functions of c :

$$z = 15\frac{20 - c}{300 - 17c} \text{ in the iron-cementite hypothesis,}$$

$$\text{and } z = 3\frac{100 - c}{300 + 11c} \text{ in the iron-carbon hypothesis.}$$

Formula (C) may be written :

$$\frac{1}{T_0} - \frac{1}{T} = A \log z \quad . \quad . \quad . \quad . \quad . \quad (D)$$

A being a constant containing the modulus of ordinarily used logarithms.

In this formula there are two constants to be determined, T_0 and A, which can be calculated by the help of the figures obtained by Carpenter and Keeling in two experiments :

$$c_1 = 0{\cdot}12 \qquad T_1 = 1504° + 273° = 1777°$$
$$c_2 = 4{\cdot}37 \qquad T_2 = 1136° + 273° = 1409°$$

Determination of T_0 and A in the $Fe_3C - Fe_3$ hypothesis.— Proceeding from :

$$z_1 = \frac{2455}{2483} \qquad z_2 = \frac{10335}{22571}$$

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[1] These formulæ allow of the values of z being deduced from those of x and y shown in the foregoing table. Thus, for $c = 3{\cdot}51$ there will be found $y = 40{\cdot}894$, from which can be deducted $z = 0{\cdot}591$.

The following results are obtained:

$$A = \frac{\frac{1}{T_2} - \frac{1}{T_1}}{\log \frac{z_1}{z_2}} = 0{\cdot}000439636$$

$$T_0 = \frac{\log \frac{z_1}{z_2}}{\log \frac{\sqrt[T_2]{z_1}}{\sqrt[T_1]{z_2}}} = 1783{\cdot}87^\circ \ (T_0 \text{ Centigrade} = 1510^\circ{\cdot}9)$$

Determination of T_0 and A on the Fe — C hypothesis.—From

$$z_1 = \frac{2497}{2511} \qquad z_2 = \frac{28689}{34087}$$

it results (using the same formulæ):

$$A = 0{\cdot}00180289$$
$$T_0 = 1790{\cdot}93^\circ \ (T_0 \text{ Centigrade} = 1517^\circ{\cdot}9)$$

It will again be seen that the difference between T_0 as calculated, and the figure 1505° obtained by Carpenter, is within the limits of experimental error on the iron-cementite hypothesis, but that this is not so in the case of the value of T_0 obtained on the iron-carbon hypothesis.

The discrepancy between the observed numbers and those obtained by the Le Chatelier-Schroeder formula are even more strongly marked so far as intermediate values are concerned. If the Fe — C constitution be accepted we can deduce from (D):

$$T = \frac{T_0}{1 + AT_0 \log \frac{1}{z}}$$

a formula which, applied to a certain number of experiments, gives the table on page 6.

Conclusions.—On examining the two tables given the following conclusions may be drawn :

1. Whether Raoult's law or Le Chatelier's formula be adopted the calculated figures agree better with the results obtained on measurements, in the case of the iron-cementite hypothesis, than in that of the iron-carbon hypothesis.

2. The results which agree best are obtained by the assumption of a rectilinear variation, which is afforded by the Fe_3C — Fe_2 hypothesis.

TABLE II.

c.	Iron-Carbon.		Iron Cementite.		T_{mes}.	$T - T_x$	$T_y - T$
	$\frac{1}{s}$	T_x.	$\frac{1}{s}$	T_y.			
Per Cent.		Degrees.		Degrees.	Degrees.	Degrees.	Degrees.
0·53	$\frac{3058\cdot3}{2984\cdot1}$	1458·4	$\frac{2909\cdot9}{2761\cdot5}$	1479·6	1473·0	14·6	6·6
0·80	$\frac{3088}{2976}$	1429·7	$\frac{286\cdot4}{264}$	1462·7	1455·5	25·8	7·2
0·93	$\frac{3102\cdot3}{2972\cdot1}$	1416·4	$\frac{2841\cdot9}{2581\cdot5}$	1454·3	1443	26·6	11·3
1·51	$\frac{3166\cdot1}{2954\cdot7}$	1359·7	$\frac{2743\cdot3}{2320\cdot5}$	1414·7	1406	46·3	8·7
1·97	$\frac{3216\cdot7}{2940\cdot9}$	1317·9	$\frac{2665\cdot1}{2113\cdot5}$	1380·3	1367	49·1	13·3
2·63	$\frac{3289\cdot3}{2921\cdot1}$	1262·3	$\frac{2552\cdot9}{1816\cdot5}$	1325·6	1305	42·7	20·6
3·03	$\frac{3333\cdot3}{2909\cdot1}$	1230·9	$\frac{2484\cdot9}{1636\cdot5}$	1288·7	1277	46·1	11·7
3·51	$\frac{3386\cdot1}{2894\cdot7}$	1195·1	$\frac{2403\cdot3}{1420\cdot5}$	1239·9	1230	34·9	9·9
3·98	$\frac{3437\cdot8}{2880\cdot6}$	1162·1	$\frac{2323\cdot4}{1200}$	1186·2	1171	8·9	15·2

PART II.

Why should it have been assumed that the iron molecule contained two atoms? The author has adopted this hypothesis in order, in the first instance, to obtain in the eutectic a number of molecules of solvent practically equal to the number of molecules of the dissolved body, and because, on the hypotheses $Fe_3C - Fe$, $Fe_3C - Fe_2$, $Fe_3C - Fe_3$, it will be found that the eutectic contains 37, 54, and 64 per cent. of cementite molecules respectively. When he had found, on the second hypothesis, so striking a degree of rectilinearity, he sought to ascertain whether it would be possible, on the other hypotheses, likewise to obtain a similar rectilinearity. Theoretically this would not be possible, for it is easy to see that if a certain value of *m* gives a rectilinear variation for the system $Fe_3C - Fe_m$, any other value of *m* would give a hyperbolic variation, but, as only an approximate rectilinearity was involved, he assumed that this argument had not sufficient weight, and he plotted curves for different values of *m*. For $m = 1$ and $m = 3$, there would be in regard to the number of molecules of cementite per cent., respectively,

$$y_1 = \frac{1400c}{300 - 31c} \quad \text{and} \quad y_3 = \frac{1400c}{100 - c}$$

formulæ by the help of which he plotted curves analogous to those shown in the figure, and corresponding with $m = 2$. The result was that the curve for y_1 was wholly below the chord joining the extreme points $c = 0{\cdot}12$, $T = 1504°$; $c = 4{\cdot}37$, $T = 1136°$, whereas the curve for y_3, after oscillating about this chord for minute values of c, passes above it for $c = 0{\cdot}53$ and persists so up to $c = 4{\cdot}37$. The curve corresponding with $m = 1$ thus presents its concavity to the upper part of the figure, whereas that corresponding with $m = 3$ has its convexity uppermost. As regards the line corresponding with $m = 2$, it can be seen, on inspecting the figure, that it oscillates above and below its chord AB, while still remaining very near to the latter. For intermediate values of *m*, starting from $m = 1$, the curves would be less and less concave as the value of *m* approximated towards 2, and then would become more and more convex in proportion as *m* became farther from 2 and nearer to 3. It would appear, therefore, that $m = 2$ (or a value very closely approximating thereto, if fractional values be admissible), which represents the value at which the *liquidus* becomes a straight line if the observations were capable of being made with mathematical accuracy.

The divergences between the observed and the calculated temperatures, on assuming rectilinear variation on the hypotheses $m = 1$ and $m = 3$, are considerable. The respective temperature is given by

$$T_1 = 1509{\cdot}698 - 10{\cdot}0497 y_1 \text{ \&c.}$$
$$T_3 = 1514{\cdot}194 - 5{\cdot}9075 y_3.$$

A few values only need be given:

c.	T_1.	T_3.	T_m.	$T_1 - T_m$.	$T_m - T_3$.
1·85	1402°·4	1358°	1383°	19°·4	25°
2·25	1372°·2	1323°·6	1350°	22°·2	26°·4

It will be seen that the differences are reversed owing to what has been said above relative to the directions of convexity of the two curves; thus, for $c = 1{\cdot}85$ the error varies from $-19°{\cdot}4$ and becomes $4°{\cdot}9$ when $m = 2$, while for $c = 2{\cdot}25$ the error varies from $-22^\circ \cdot 2$ to $+26^\circ \cdot 4$ and becomes $5^\circ \cdot 1$ when $m = 2$.

Direct Calculations of the Value of m giving a Rectilinear Variation.—It is possible directly to calculate the value of m giving rectilinearity as follows:

Let m be an unknown quantity in the expression $Fe_3C - Fe_m$ the number y_m of molecules of cementite per cent. is given by

$$y_m = \frac{1400mc}{300 + (14m - 45)c}.$$

The extreme values

$$c' = 0 \cdot 12 \qquad T' = 1504^\circ$$
$$c'' = 4 \cdot 37 \qquad T'' = 1136^\circ$$

correspond respectively with

$$y'_m = \frac{1400m}{14m + 2455} \text{ and } y''_m = \frac{1400m}{14m + 23 \cdot 65}.$$

Equating for the straight line connecting the points

$$y'_m T' \text{ and } y''_m T'',$$

and substituting for y_m the value given above we have

$$\frac{14m + 23 \cdot 65}{14mc + 15(20 - 3c)} = \frac{0 \cdot 243135}{92} \cdot \frac{1504 - T}{c - 0 \cdot 12},$$

Reducing the right-hand expression which is independent of m, we get

$$k = 0 \cdot 00264277 \cdot \frac{1504 - T}{c - 0 \cdot 12} \quad . \quad . \quad (a)$$

and solving the equation in respect of m, we have:

$$m = \frac{15k(20 - 3c) - 23 \cdot 65}{14(1 + kc)} \quad . \quad . \quad (\beta)$$

The formulæ a and β allow of a value being ascribed to m, which is such that the characteristic point in the experiment shall, for each experiment conditioned by c and T, be situated along the straight line which joins the extreme points.[1] Thus for:

$$c = 0 \cdot 8, \ T = 1455^\circ \cdot 5,$$

we get

$$k = 0 \cdot 18849 \text{ and } m = 2 \cdot 196;$$

and similarly, if $c = 2 \cdot 25$, and $T = 1350^\circ$, we get $k = 0 \cdot 19107$ and $m = 1 \cdot 795$.

Repeating this calculation for the different experiments carried out by Carpenter and Keeling, it will be seen that the whole number which best corresponds is $m = 2$.

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[1] It should, of course, be understood that the positions of these extreme points are likewise unknown, and will depend on the value for m which is to be obtained.

Is it possible, in the iron-carbon hypothesis, to obtain a rectilinear variation on the assumption that one of the constituents contains several atoms in its molecule? In the iron-carbon theory we find a non-rectilinear variation on assuming that the molecules of the two constituents are composed of a single atom,[1] but the question might still be asked: Would it not be possible to obtain rectilinearity by assuming that the molecule of one of the constituents—iron, for example—was composed of several atoms?

In other words, cannot the system $Fe_m - C$ give a rectilinear variation from any suitably chosen value of m?

This is the point which remains to be considered. Assuming the alloy contains an x_m group C, and a $100 - x_m$ group Fe_m, we have:

$$x_m = \frac{1400mc}{300 + (14m - 3)c}$$

and for the experimental extremes ($c' = 0{\cdot}12$ and $c'' = 4{\cdot}37$)

$$x' = \frac{1400m}{14m + 2497} \quad \text{and} \quad x'' = \frac{1400m}{14m + 65{\cdot}65}.$$

Equating as before for the straight line which connects these extreme points, and substituting for x_m its value, we have

$$\frac{14m + 65{\cdot}65}{14mc + 3(100 - c)} = 0{\cdot}00264277 \cdot \frac{1504 - \mathrm{T}}{c - 0{\cdot}12} = k;$$

k thus having the same value, for a given experiment, as in the iron-cementite hypothesis. Taking m' as the value of m deduced from this equation, we have

$$m' = \frac{3k(100 - c) - 65{\cdot}65}{14(1 - kc)} \quad . \quad . \quad (\gamma)$$

and on comparing the value γ with the value β, it will be seen that $m' = m - 3$.

That is to say that in the $Fe_m - C$ hypothesis the value of m which gives rectilinearity is obtained by subtracting three units from that which gives rectilinearity in the $Fe_m - Fe_3C_4$ hypothesis. Now, on the latter hypothesis rectilinearity was obtained for $m = 2$. It follows therefore that $m' = -1$, which means that it is impossible to obtain rectilinear variation, on the iron-carbon hypothesis, with *any* value of m.

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[1] Or of the same number of atoms.

CORRESPONDENCE.

Professor H. C. H. Carpenter, F.R.S. (Royal School of Mines), wrote expressing his thanks to Professor Cesàro for his valuable note on "The Liquidus in the Iron-Carbon System." Professor Cesàro, a distinguished scientist and President of the Belgian Academy of Sciences, had spent some time working in his (Professor Carpenter's) laboratories. During that period they had frequently discussed the iron-carbon equilibrium, and Professor Cesàro's note was the result of some of their discussions. The point dealt with was one of very considerable interest and importance, and the mathematical analysis to which Dr. Cesàro had subjected the experimental results obtained by Mr. Keeling and the writer some fifteen years ago, led to the interesting conclusions stated in the note. Professor Cesàro had approached and treated the subject in a broad philosophical and strictly scientific way, which was much to be commended, and considerable weight attached, therefore, to his conclusions.

ON THE NON-ALLOTROPIC NATURE OF THE A2 TRANSFORMATION IN IRON.

By KÔTARÔ HONDA (Tohoku Imperial University, Sendai, Japan).

1. In recent years there has been a considerable amount of discussion[1] as to the nature of the A2 transformation. The present author communicated a paper on the same subject[2] at the Annual Meeting of the Iron and Steel Institute, 1915, and showed that, unlike the A1, A3, and A4 changes, the A2 transformation does not take place at a definite temperature or within a small range of temperature, called the critical point or range, such as 768°, but that it begins even at ordinary temperature, its rate becoming greater as the temperature is increased, until it is completed at 785°. All physical properties, such as the heat absorption (or evolution)—the change of specific heat—the intensity of magnetisation, electric resistance, thermal conductivity, magnetic expansion, mechanical properties, &c., vary therefore similarly with each other, their magnitudes changing slowly at lower temperatures, and the change becoming faster as the temperature approaches 785°. On the other hand, the A1, A3, and A4 transformations take place within a small range of temperature, and therefore are of a different character; hence the author concludes that, from the standpoint of the phase doctrine, β-iron is not an independent phase but should be included in the α-phase. From the discussion on his paper, and also from other papers, it will be found that, generally speaking, American metallurgists consider the A2 transformation to be an allotropic change, and β-iron as an independent phase, while those of England and the Continent do not recognise β-iron as a distinct phase. Some metallurgists contend that the question, whether the A2 transformation is an allotropic change or not, is a matter of definition, having in itself little importance. In

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[1] G. K. Burgess and J. J. Crowe, *Scientific Papers, Bureau of Standards* (1914), No. 212; C. Benedicks, *Journal of the Iron and Steel Institute*, 1914, No. I. p. 419; K. Honda, *Journal of the Iron and Steel Institute*, 1915, No. I. p. 198.

[2] On the nature of the A2 transformation in iron.

the present communication, it will be conclusively shown that the A2 transformation differs essentially in its nature from the A1, A3, A4 transformations, and cannot be considered as a change of phase in a proper sense of words.

2. If a homogeneous substance be taken and heated to a high temperature, it will, in some cases, undergo an internal change at a certain high temperature, whereby all its physical properties change to a greater or lesser degree. The substance is then said to be changed from one phase to another, or to have undergone an allotropic change. Such a transformation of a substance may be surmised from an abrupt change of one or more physical properties at a certain temperature. Considered from the standpoint of the molecular theory of matter, an allotropic change may be understood in the following way. A substance has a given molecular or atomic configuration, the molecules or atoms being in a state of stable equilibrium under the mutual action of molecules making thermal vibrations. As the temperature increases, this thermal vibration becomes greater in amplitude, and when the temperature attains a certain value the amplitude of vibration is supposed to become so great that the molecules or atoms are no longer in equilibrium under the original configuration and take on a new configuration of stable equilibrium. This abrupt change of configuration is in fact an allotropic change. Since the properties of a substance depend on the molecular or atomic configuration, all properties must alter by the change of configuration or by an allotropic change.

Since every transformation takes a certain time, that is, is accomplished with a certain velocity, it is natural to suppose that for a transformation to be completed a certain time is required, depending on the nature of the transformation. Hence it is evident that though at ordinary rates of heating or cooling an allotropic change takes place gradually in an interval of temperature, yet it will occur at a definite temperature if sufficient time be allowed for the transformation.

Almost all the physical properties of every homogeneous substance which does not undergo any transformation will continuously change if the substance be heated to high temperatures, as, for example, thermal expansion, thermal conductivity, specific heat, electric resistance, and mechanical properties, all of which vary with increasing temperatures. There are but few properties which undergo no change at high temperatures. During heating and cooling there are also gradual heat absorption and evolution respectively; because every substance has a definite amount of specific heat at each temperature, and therefore this heat must be absorbed during heating or given off during cooling, for a rise or fall of one degree of temperature. Thus, by heating or cooling an iron rod, heat will be absorbed or evolved for all temperatures from room temperature to the highest. If, however, the specific heat does not vary much with temperature it is very difficult to detect, by thermal analysis, the heat thus gradually evolved or absorbed.

Again, in actual cases, the physical properties of a substance undergoing an allotropic transformation will change, not continuously, but more or less abruptly, in the temperature-range of transformation, with an absorption or evolution of heat. What is then the difference between the gradual change accompanying an increasing temperature in non-transformable substance and an allotropic change of a substance? At first sight the difference seems to consist only in the rate of change of physical properties with respect to temperature. If such be the case, the two kinds of transformations just referred to differ only quantitatively from each other, and there is no essential difference between them. In an extreme case of a discontinuous change, we have doubtless to consider it an allotropic transformation; but where a change takes place only gradually, it is very difficult to decide whether the change is allotropic or not. A study of these transformations shows, however, that there is an important difference, which characterises one transformation from the other. Thus in a change of non-allotropic nature, if the temperature be given, physical properties are perfectly determinate—that is, they are definite functions of the temperatures. Hence, if the thermal equilibrium be once established, the change in a property of the substance caused by change of temperature does not increase by a prolonged heating. In an allotropic transformation, however, the change of a property may at an ordinary rate of heating or cooling take place in an interval of temperatures; but if the substance be kept at a transforming temperature for sufficiently long, the change of property—that is, the transformation of the substance, will take place at that temperature. The author considers this the sole criterion for distinguishing the one transformation from the other. Hence the definition of an allotropic change may conveniently be given as follows: *An allotropic change is the transformation of a substance from one phase to another, which proceeds at a definite temperature, if a sufficient time be allowed for the transformation.*

3. In a former experiment[1] the author proved magnetically that the A2 transformation in pure iron is perfectly reversible during heating and cooling, and that, although the temperature be kept constant in every point in the heating or cooling curve for a sufficiently long time, it does not progress with time—that is, every stage in the A2 change is a definite function of temperature. Hence, if in the said transformation a particular point or range be considered as a point or range of an allotropic change or a phase-change, any other point or range may also be considered as a similar point or range, so that we would obtain an infinite number of phases below the critical temperature. Hence the A2 transformation cannot be considered as an allotropic change of phase in a proper sense of words.

What kind of internal change then is the A2 transformation? To answer this question it is necessary to introduce a molecular theory of magnetism, which explains the transformation of a ferromagnetic substance to a paramagnetic at high temperatures, or the A2 transformation. According to joint papers[2] by Assist. Prof. J. Ôkubo and the present author, the said transformation may be explained in the following way: The temperature affects magnetisation in two opposite ways; the first effect, which is specially conspicuous in weak fields, but which vanishes in strong fields, is to increase the magnetisation, while the second effect is always to decrease it. The molecules of a ferro-magnetic substance are continuously making axial rotations about their magnetic axis, and at the same time small vibratory rotations about the axes perpendicular thereto. The first motion explains the diminution of magnetisation with the rise of temperature—the A2 transformation—while the second motion explains its increase in weak fields and has no connection with the A2 transformation. Since these motions are considered to be dependent on the translational thermal vibrations of the molecules, their energies are supposed to be far less than those corresponding with the equipartition of energy. At ordinary temperature, the energy of rotation about the magnetic axis is considered to be very small, but as the temperature rises it rapidly increases, its rate of increase becoming steadily greater. As the molecules acquire the greater amount of rotational energy, the gyrostatic action of the molecules increases, and therefore, under a magnetic force, the substance becomes less and less magnetisable. At the critical point, the rotational energy will be so great that the gyrostatic action of the molecules becomes sufficient to change the ferromagnetic substance to the paramagnetic. It is here necessary to assume that when the magnetic field is released, the axes of the gyromolecules take, by thermal impacts, a uniform distribution in all directions. Thus, according to the above theory, the A2 transformation is not a change of molecular configuration or a change in the molecule, but the process of acquiring the rotational energy of molecules, whose amount is a definite function of temperature.

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[1] *Science Reports of the Tôhoku Imperial University*, 1916, vol. v. p. 285.
[2] *Ibid.*, 1916, vol. v. p. 325; *ibid.*, 1918, vol. vii. p. 162.

It is here to be noticed that the critical or A2 point, as determined thermally, is usually taken as 768° C.; this is the temperature at which the rate of heat evolution or absorption is at a maximum on cooling or heating respectively, and somewhat lower than 785° C. proposed by the present author.[1] The latter is, of course, not the temperature at which the A2 transformation would take place but the temperature at which the A2 transformation begins on cooling, or terminates on heating. *It is the temperature at which iron changes from the ferromagnetic to the paramagnetic state.*

4. In the case of pure iron there are, besides the A2 transformation, two others, the A3 and A4 transformations. That the last two transformations will take place at definite temperatures, if a sufficient time be allowed for the transformations, is magnetically proved by the experiments of T. Ishiwara [2] and T. Terry.[3] In the experiment made by Mr. T. Ishiwara, the

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[1] *Science Reports of the Tôhoku Imperial University*, 1913, vol. ii. p. 59; *ibid.*, 1916, vol. v. p. 285.

[2] *Ibid.*, 1917, vol. vi. p. 133.

[3] *Physical Review*, 1917, vol. i. p. 394.

heating and cooling for the A3 transformation were conducted at an extremely slow rate. This transformation by cooling actually took place at 898°, and the difference between the Ac3 and Ar3 points did not exceed five degrees. Fig. 1 shows an example of the result obtained by him. Here the complete transformation required about three hours. The A4 transformation takes place much more rapidly than the A3 transformation; by keeping the temperature constant at 1390°, the A4 transformation[1] takes place in a few minutes (Fig. 2). Hence A3 and A4 transformations are properly called allotropic changes of phase.

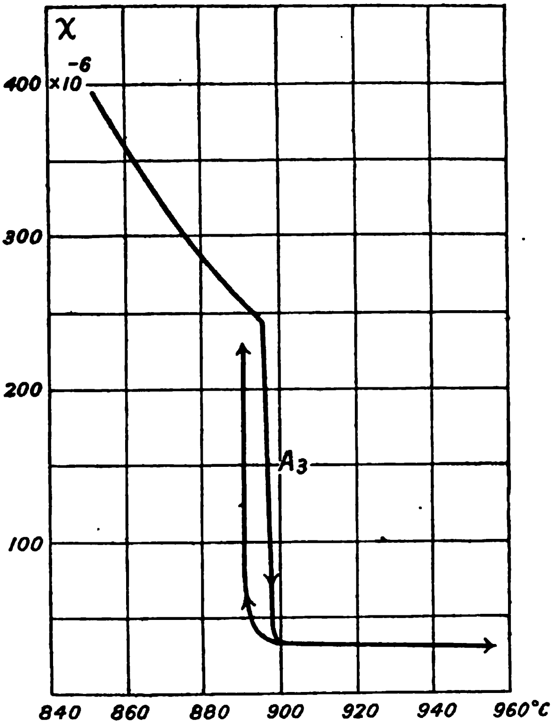

Fig. 1.—The A3 Transformation in Pure Iron.

In the case of carbon steels there are, in addition to the above, two transformations A0 and A1 at 215° and 700°–750° respectively. The former is the critical point of cementite[1] (Fe_3C) present in the steel and of exactly the same nature as the A2 transformation above discussed. The latter is a eutectic transformation of cementite and ferrite; it has been magnetically proved by the present author[2] that the Ac1, Ar1 transformations really take

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[1] *Science Reports of the Tôhoku Imperial University*, 1917, vol. vi. p. 133.

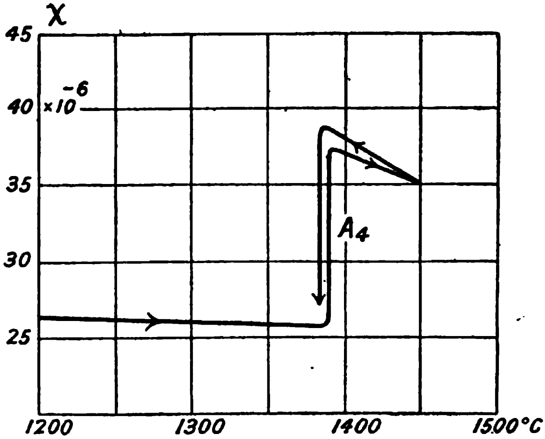

Fig. 2.—The A4 Transformation in Pure Iron.

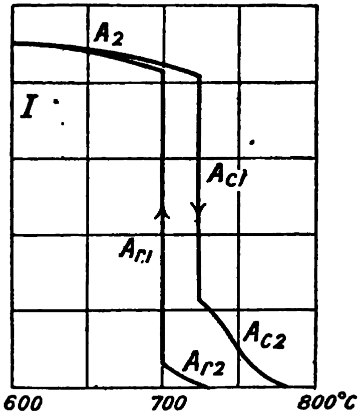

Fig. 3.—Carbon Steel 0·8 per Cent. C.

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[1] *Science Reports of the Tôhoku Imperial University*, 1913, vol. ii. p. 203; *ibid.*, 1917, vol. vi. p. 23.

[2] *Ibid.*, 1916, vol. v. p. 285.

place at definite temperatures, if the rate of heating or cooling be sufficiently slow (Fig. 3). Hence the A1 transformation is properly called a change of phase.

The following are the conclusions arrived at:

1. In the case of pure iron, there are three transformations, A2, A3, and A4. The two latter are allotropic transformations, while the first cannot properly be called an allotropic change of phase.

2. In the case of carbon steels, in addition to the above, there are two transformations, A0 and A1. The latter is a change of phase, while the former is a change having the same nature as the A2 transformation.

3. The A0 and A2 transformations are internal changes extending from the critical temperature to the lowest; every stage of these changes is a definite function of temperature. From the standpoint of the molecular theory of magnetism, these transformations may be regarded as processes in which the molecules acquire rotational energy about their magnetic axes.

CORRESPONDENCE.

Professor H. M. Howe, Honorary Vice-President, wrote: Professor Honda's contention that the A2 change is not allotropic is based essentially on the second and third phrases in his definition, limiting allotropic changes to those "which proceed at a definite temperature, if a sufficient time be allowed," meaning by "proceed," "complete themselves."

Looking at the matter perfectly pragmatically, we naturally ask the learned author what it profits thus to split up changes of this general class into two divisions, one called allotropic which complete themselves at a definite temperature, and others to be called by some other name not yet proposed which do not? We have been accustomed to regarding the essence of allotropy as "a change in one or more, usually in most, of the properties of an element not caused by a change of state." I do not insist on the precise wording of the definition, but only on its general meaning. That, I take it, is the established meaning of allotropy, and has been since allotropy was first proposed by Berzelius. I for one object strongly to introducing such changes in the established meaning of scientific words unless some decided good is to be gained.

Even if we accept the explanation of the A2 change which the author gives on p. 460, what reason does it give for excluding such changes from the class "allotropic"?

Let us remember the function of language, to convey thought. This function is interfered with if the established meanings of words are changed, especially if the change is arbitrary, as it seems to be in the present case. This desired stability of language in no way conflicts with the need of adding new words whenever the advance of scientific thought gives us a new conception for which no fit word exists.

Dr. A. McCance (Glasgow) wrote that among those who had studied the question the non-allotropic nature of A2 was generally recognised, but Professor Honda's paper showed that there was still some difficulty in so defining allotropy that A2 was properly excluded while A3 and the less known A4 were included as true allotropic changes. The criterion proposed by Professor Honda that an allotropic change took place at a definite temperature if sufficient time were given for the transformation, would, he feared, not remove the existing confusion. Whereas in the case of A3 an appreciable time was required for complete equilibrium, the A2 point was the culmination of changes which commenced at lower temperatures and which appeared to reach equilibrium at any temperature instantaneously. The difference between them was thus only one of degree and not of kind, and referred the question to the available degree of experimental skill. A definition based on such postulates could therefore never be permanent. He (Dr. McCance) had always maintained that the only definition which was free from ambiguity and covered all cases was when allotropy was defined as "a change in crystalline symmetry." The possible systems of crystalline symmetry were limited, and once the symmetry in any case was known there could be no doubt, so that that definition made an unalterable and final decision.

That definition also included without further extension those cases of dynamic allotropy studied by Smits, since they fell naturally into the category of mixed crystal systems of one component.

Professor C. **Benedicks** (Stockholm) wrote expressing his view that Professor Honda was quite right to emphasise that the nature of the A2 transformation was not a matter of definition only, and in pointing out that "β" was not an independent phase but should be included in the α phase. That view was put forward by Professor H. Le Chatelier and by P. Weiss, and was dealt with in some detail by Professor Benedicks in 1912 and 1914, and by Professor Honda in 1915.[1] It was also of historical interest to recall that Osmond as far back as 1906[2] had come to the conclusion, based on determinations of the electric resistance, that the A2 transformation extended to the lowest temperatures, as was now concluded by Professor Honda as the result of the valuable magnetic experiments carried out in his laboratory.

Broadly the views of Professor Honda and of Professor Benedicks agreed, except in regard to a minor detail. Professor Honda propounded a new theory as to the cause of the transformation of ferro-magnetic iron and para-magnetic iron at A2, namely, that the disparition of ferro-magnetism was due to a gyroscopic action. He (Professor Benedicks) still accepted as an explanation of the phenomena the Lange-vin-Weiss theory. That theory held that owing to the thermal vibrations (not rotation) of the atoms, the parallel orientation in "swarms" which was admittedly necessary at high temperatures for the ferro-magnetic state was not possible. Further, the occurrence of allotropy presupposed that the atoms of a substance were capable of existing in two different states of internal equilibrium: M and N, which were generally temperature functions. When M predominated, the substance was spoken of as the μ phase, while when N predominated, the substance was described as the ν phase. For instance, if a given substance consisted at 144·5° C. of 99 per cent. M and 1 per cent. N, and at 145·5° C. consisted of 1 per cent. M and 99 per cent. N, it would be said that an allotropic transformation point occurred at 145° C., at which practically the atom was transformed from state M to state N. On that point all observers could be said practically to agree.

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[1] *Journal of the Iron and Steel Institute*, 1912, No. II., 1914, No. I., and 1915, No. I.

[2] *Revue de Métallurgie*, 1906, Vol. 3, p. 551; *Journal of the Iron and Steel Institute*, 1912, No. II., p. 260.

The theory which he (Professor Benedicks) had proposed in 1912 was, without requiring any special hypothesis, more general. It agreed with that of A. Smits, who said that in such an instance the definite allotropic transformation point at 145° C. could subsist, even in a case where at 144·5° C. the substance consisted of, for example, 75 per cent. M and 25 per cent. N. Such a possibility would be rejected *a priori* but had to be taken into consideration if unduly narrow conclusions were to be avoided. He (Profesor Benedicks) quite admitted that at a temperature just below A3 the metal by no means contained 99 or 100 per cent. of M, but a considerably smaller percentage of "m," and that the percentage of M at temperatures increasing from low temperatures continuously decreased from 100 to "m" per cent., in other words, iron with rising temperature contained a quantity of "γ-atoms" which steadily increased up to a temperature just below A3, when it suddenly changed to nearly 100 per cent. He thought that that hypothesis of the solubility of the bulkier γ-iron in α-iron was necessitated more particularly by the behaviour of the dilatation curve of pure iron; indeed no other explanation had as yet been given of the remarkable concavity of the dilatation curve towards the temperature axis, which was conspicuous from about 700° C.[1] That continuous increase of "γ-atoms" in the "α-iron" on heating would have an influence on the magnetic loss (A2) which would superpose itself on the thermal agitation (vibrations). Further, as the γ-atoms were known to crystallise together more easily with foreign substances than the "α-atoms" (solubility in "γ-iron" greater than in "α-iron"), it was natural to admit that the occurrence of "γ-atoms" in solution in the β interval would on cooling facilitate the retention of impurities such as carbon in a dissolved state, which would give rise to further thermal irregularities, such as were known to exist in iron of commercial qualities. That solubility of the two modifications was not taken into consideration by Professor Honda, whose theory might therefore afford a simpler explanation. The chief value of a theory was not that it should be as simple as possible, but that it should account for known facts, which, as in the present instance, and in the case of dilatation, were somewhat complicated.[2] In regard to essentials, however, the opinions of Professor Honda were in close agreement with his own.

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[1] *Journal of the Iron and Steel Institute*, 1912, No. II., p. 264.

[2] Certain thermoelectrical phenomena which he (Professor Benedicks) had described in the *Journal* for 1916 (No. I., p. 211) could hardly be explained without taking into consideration the assumed solubility of the modifications.

THE EXPERIMENTAL INVESTIGATION OF THE INFLUENCE OF THE RATE OF COOLING ON THE HARDENING OF CARBON STEELS.

By A. M. PORTEVIN and M. GARVIN (Paris).

PART I.

EXPERIMENTAL INVESTIGATION OF THE COOLING OF DIFFERENT METALS BY IMMERSION IN WATER.

INTRODUCTION.

The results of all experimental work can ultimately be expressed either numerically or graphically. The degree of confidence that can be placed in such results depends principally on the precautions taken during the tests, on the nature of the measuring instruments, and on the arrangement of the apparatus employed. It is these manipulative details which, far more than the general preconceptions underlying the investigation (which are seldom novel), determine the extent to which the investigator's results can be accepted. Measurements badly carried out may yield erroneous results not, at first sight, distinguishable from accurate results. It is therefore necessary minutely to detail the experiments and measurements made, in order to enable other people to judge the results with full knowledge as to how they were obtained, and to enable them to repeat the experiments at will, in order to check the results given. In the authors' opinion, these details are too often passed over in silence, as though they were negligible, although this prevents all attempts at verification and prohibits discussion. For this reason they have deemed it advisable to describe the whole of the details of the processes employed, so as to enable the reader to follow the sequence of operations as though he were, so to speak, present while they were being carried out. He will then be able not only to take into consideration the precautions observed, but also to note those which, in his opinion, have been neglected, which will enable him to criticise the whole of the results intelligently. No further apology is therefore needed for the space given in the following paper to descriptions of the experimental appliances, as such descriptions possess vital interest and can never be too complete.

A. MODE OF USING THE THERMOCOUPLES.

The experimental investigation of rapid variations in the temperature of a piece of metal, such as those which result from the operation known as "quenching," presents a considerable amount of difficulty, particularly when it becomes a question of samples of very small dimensions. Of these difficulties the greatest is, undoubtedly, that of avoiding too great differences of temperature between the thermometric body and the point within the sample under investigation.[1]

The use of a thermo-electric couple which is, from every point of view, so convenient that it is difficult to imagine any better instrument, must be subordinated to the taking of precautions capable of diminishing the following causes of error, which may lead to a considerable divergence between the temperature of the junction and that of the mass of metal:

1. Imperfect continuity, from the point of view of calorific conductivity, between the couple and the sample.
2. Transmission of heat by the conductivity of the wires of the couple, which may make the temperature variations, occurring at the junction, affect a considerable length of the wires.
3. Thermal inertia of the juncture.
4. Thermal inertia of the necessary insulation.

These different points will be discussed in succession.

1. In the bulk of the experiments carried out up to the present their authors have not overlooked the necessity of securing proper exchanges of heat between the piece quenched and the thermometric body. Generally speaking, however, they have contented themselves with bringing the junction of the thermocouple into contact with the bottom of the orifice made in the sample—an operation which they did not subject to any verifi-

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[1] It is impossible in any case to eliminate entirely the perturbational influence of the thermometric body, but it is essential to reduce it by every means available.

cation either at the commencement of the experiment or during its progress. The subsequent heating might therefore affect or even destroy that contact:

(*a*) By the play of the dilatations.

(*b*) By the formation of oxide, if the sample be oxidisable.

Further, in the arrangement of the appliances hitherto adopted, the sample, clamped to the end of a holder, was moved, together with the latter, so as to pass from the furnace to the quenching bath. Such movement may similarly lead to changes in the degree of contact in question. It was the above considerations which led the authors to adopt the arrangement described later, in which the sample remains fixed while the appliances for heating and quenching are movable. The contact with the couple is maintained as closely as possible, the holder being independent of the dilatations, and contact depending on the actual weight of the thermo-electric appliances. At the same time an electrical arrangement for checking the existence of the contact throughout the operation was employed. For this purpose it was only necessary to close, by means of a small key, the circuit from a high internal-resistance battery interpolated across one of the wires of the couple, and traversing the contact of the hot thermo-junction with the bottom of the sample, and to observe—by means of a dial galvanometer indicating the temperatures during the heating—the ohms lost during the passage of the current.[1] The terminals of the battery being thus connected up in the direction required, and with the interposition of the key, one with the sample (that is to say, with practically the entire system for heat-treating the sample), and the other with one of the cold connections of the thermocouple, current from the battery flows on closing the key, if the contact between the thermocouple and the sample be satisfactory, and the needle of the galvanometer is deflected. If the contact is imperfect the current cannot pass, or is weakened, and this is shown by the galvanometer readings.

From the physical point of view, the authors have found it absolutely necessary thoroughly to clean the cavity which receives the thermocouple, not only to ensure that the circuit control acts properly but also to avoid any injury to the thermocouple.

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[1] It might have been preferable to employ an accumulator battery or a battery incapable of becoming polarised, and of fair capacity, in series with a suitable resistance apparatus.

For this purpose the cavities in the samples were freed from grease by injecting benzene and ether in succession, so as to remove particles resulting from the drilling and to dissolve any greasy substances. The liquids were expelled by strongly shaking the sample, which was then dried at a low temperature. Finally, a grease-free rimer was used to clear out the bottom of the cavity and to remove any oxide that might have been formed, particularly when the sample had already undergone previous tests.

The authors found, however, in the case of samples that cracked, that the oxidisation after quenching was practically *nil*, the air not being able appreciably to renew itself within the cavity.

In order to ascertain the efficacy of the precautions taken, cooling curves have been plotted in respect of the same sample (of silver, $d = 8$) with (*a*) a perfect contact, and (*b*) with the thermocouple slightly raised, so as not to rest upon the bottom of the cavity. Fig. 1 shows the two curves obtained. They have nothing in common with each other, and afford an idea of the degree of magnitude of the errors which may arise from lack of the precautions described.

2. The influence of the thermal conductivity of the wires of the thermocouple is as follows. The couple being heated throughout a portion of its length at the commencement of the quenching, and the temperature of the sample being rapidly lowered, the wires become cooled by, on the one hand, convection, and on the other by conductivity. Part of the heat flows from the wires to the sample across the junction, and the temperature of the latter may be appreciably raised if the amount of heat so transmitted be considerable. The authors were led, therefore, to employ the thinnest wire that can be made, short of risking an undue degree of brittleness. A diameter of 0·1 mm. was adopted as suitable, notwithstanding that a thermocouple of this gauge is somewhat difficult to manipulate.

To begin with, a few experiments were made in order to ascertain the time required to attain equilibrium in a thermocouple, in terms of the diameter of its wires. The arrangement employed was as follows:

A small shelf sliding along two grooves was attached to a stretched spring, and kept in position by means of an electro-magnetic release. On releasing the spring the shelf slid, practically instantaneously, over a distance of about 30 mms. This shelf carried a small electric furnace formed of a silica tube wound, for a portion of its length, with insulated constantan wire traversed by a current. The interior of this furnace was, at its hottest part, at a temperature of about 150° C. The couples, which were of constantan-wrought-copper wires of different diameters, either coiled or bent and laid in the axis of the furnace, one of the wires in the latter case being carried in a thin glass tube. The spring being in tension, the junction of the couple was placed at the heated part. The recording cylinder was then started, and at a given moment the shelf was released automatically by means of a contact pin on the recording cylinder (see below). The junction of the couple thus passed suddenly from the warm region of the silica tube to a cold region.

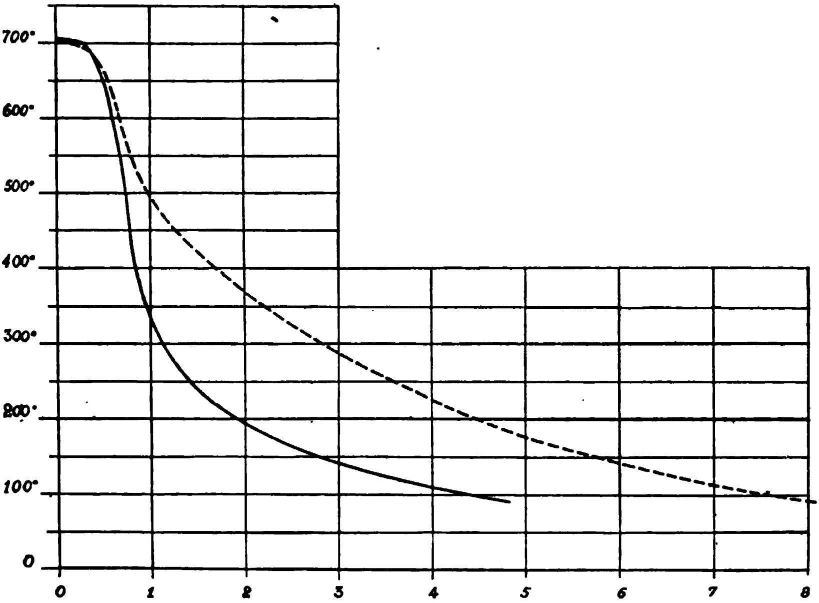

FIG. 1.—Influence of the Position of the Thermocouple in the Sample.

The accompanying curves (Figs. 2 and 3) allow of the length of time required for the equilibrium of couples of different diameters to be attained, to be found on simple inspection.[1]

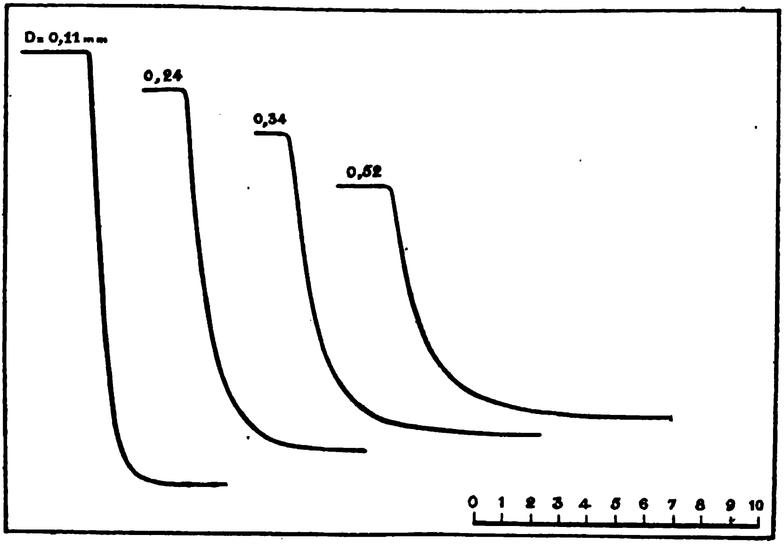

Fig. 2.—Cooling Curves for Couples at different Diameters.

Fig. 4 gives the times for attaining equilibrium to within about 1

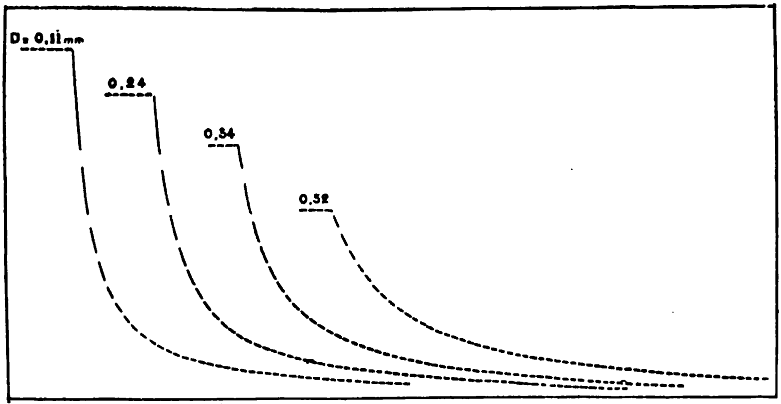

Fig. 3.—Cooling Curves for Couples at different Diameters.

or 2 per cent. for stretched and uninsulated couples (curves of

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[1] The initial and final temperatures differ from one couple to another, owing to the relative values of the effects of conductivity in the wires.

Fig. 2), and within about 2 per cent. for coiled and insulated couples (curves of Fig. 3). The influence of the thermal capacity of the insulating material is brought out by the fact that, in the case of the latter, the temperature points assume practically a straight line which does not cut the original, as was the case with the former.

It should be noted, in this connection, that the heat exchanges take place only through the air and the wires of the couples, which explains their relative slowness. The present instance differs widely from what occurs during the quenching experiments. These incidental investigations appear of interest to note, if only to induce other experimenters to renew them in similar cases.

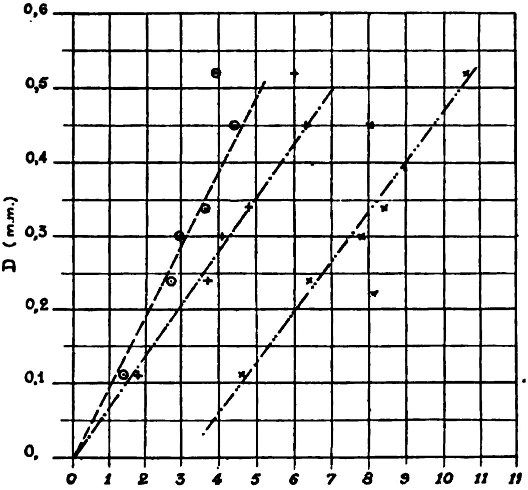

FIG. 4.—Time required to establish Equilibrium between the Couples.

3. The thermal inertia of the junction itself was reduced to a minimum by making its mass as small as possible.

To attain this result the junction was made as follows. The two wires of the couple were fastened together near their ends, in parallel, the ends being heated until fusion commenced (in a Meker blowpipe jet, which, in view of the thinness of the wires, easily accomplished this result).

The button obtained, the diameter of which was hardly larger than that of the two wires together (0·2 mm.), was then cut across in the middle by means of sharp scissors. This somewhat delicate operation gave the extremity of the couple the shape shown in Fig. 5. This arrangement has likewise the advantage of affording an appreciable supporting surface for the end of the couple and so facilitating the heat exchanges.

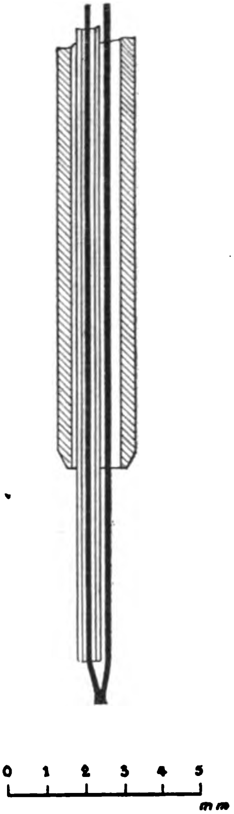

Fig. 5.—Terminal of the Thermo-electric Needle,

4. The thermal inertia of the insulant can only be reduced by making its mass as small as possible. For this purpose the authors mounted the couple between two silica tubes. The larger tube, of translucid silica and of an external diameter of about 2 mms., contained, as shown in Fig. 5, the couple, one of the wires of which was protected by a transparent silica tube of 0·6

mm. external diameter, fitting into other, slightly wider, tubes covering the joints. A strand of asbestos inserted in the external tube at the end away from the junction served to tighten up the whole arrangement. The thin tube projected about 1 centimetre at the junction end, and may be regarded as being the only one concerned, from the point of view of thermal inertia.

B. CONDITIONS NECESSARY TO SECURE CORRECT RECORDS.

The precautions necessary to ensure, as far as possible, equality of temperature between the junction of the couple and the bottom of the cavity in the sample with which it should be in contact, have already been described. It will now be necessary to discuss the conditions to be fulfilled in order to secure a sufficiently accurate record of the values of the electromotive force in terms of the times. The question arises at first as to whether the curve to be recorded should be that of electromotive force-time, or the curve derived therefrom. From a mathematical point of view this might appear an idle question, as either curve might theoretically be deduced from the other. Experimentally, however, it possesses some importance, as the sharpness with which certain sudden alterations in the direction of the curve (particularly when the transformation points are being passed) can be defined, varies according to which of these two modes of representing them is adopted. The shape of the surface affected being strictly limited, and the curve traced exhibiting a certain thickness and inevitable irregularities which might mask little details, it can hardly be doubted that an accurate derived curve would be far more advantageous, as it would allow:

1. The temperature-time curve to be obtained with sufficient accuracy and without difficulty, whereas the inverse operation is exceedingly delicate and requires the greatest precision.
2. The slightest peculiarities in the temperature-time function can be easily perceived, and their nature ascertained.
3. The points of peculiarity corresponding therewith can be recorded graphically.

Unfortunately, it happens, chiefly owing to the use of apparatus which has been insufficiently thought out or is ill-adapted to the purpose to which it is put, that the derived curve can only be obtained somewhat inaccurately, owing to supplemental causes of error, which are often considerable, introduced by the shunt transformer apparatus intended to supply the shunt circuit with electromotive force.

As it would not be proper in an investigation such as the present to rest content with a rough approximation, it appeared better to the authors to register the direct electromotive force-time curve rather than the derived curve, if only for the sake of simplifying the experimental arrangements.

The apparatus ordinarily in use in commercial laboratories are quite unsuitable for registrations of this nature. It is, as a matter of fact, necessary to satisfy the conditions given below, and already described by Professor H. Le Chatelier, some of which are somewhat contradictory.

1. The resistance of the circuit (couple-galvanometer-coil) must be high enough to allow of variations in the resistance of the wires of the couple, and any perturbations resulting from the passage of a current of too high an intensity, to be ignored.

2. The oscillation period of the free galvanometer must be very small in comparison with the total duration of the phenomena to be recorded.

3. The damping down should be to an extent approximating, so far as possible, to the critical value.

4. The sensitiveness must be sufficient to afford a curve of fairly large dimensions, upon which readings are easy and measurements accurate.

The experiments of Benedicks,[1] which are remarkable from more than one point of view, were particularly carefully conducted in all matters connected with the recording apparatus. The present authors do not, unfortunately, possess apparatus similar to that used by Benedicks, and were compelled to adapt such instruments as were available to the special circumstances. The galvanometer used was of the moving coil type, and possessed the following constants:

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[1] *Journal of the Iron and Steel Institute*, 1908, No. II.; *Revue de Métallurgie*, 1909, vol. vi.

Resistance of the coil	90 ohms
Period of one double oscillation of the coil outside the field	0·095 seconds

The magnetic field was created by an electro-magnet supplied by a battery of accumulators.[1] This electro-magnet, which was kept cool by a stream of water, was only excited while the recording lasted, in order to avoid the effects of the heating of the coil and of the iron core, a degree of excitation which, although in the circumstances employed, was only small, it would have been a matter of difficulty to take into account for the purpose of making a correction. The coil, which was of enamelled copper wire 0·04 mm. in diameter, was very open, and was suspended by two flat wires of phosphor-bronze. It carried a thin plane mirror, slightly prismatic, silvered on the back, and 4 mms. in diameter.[2] A lamp, placed in series with the winding, reduced the intensity to 0·6 ampere instead of 1·5 ampere, the amperago for which the appliance was designed.

Fig. 6 shows the electro-magnet[3] and the galvanometric apparatus dismounted (on the right of the figure). Such a galvanometer, for which, perhaps, slight improvements might be devised, realises fairly well the requirements enumerated above.

The deviation of the spot, with the authors' platinum-platinum-rhodium couple, was about 25 cms. at a distance of 1 metre, for a temperature difference of 1000° between the junctions; the total resistance of the circuit was about 350 ohms, which is an amount in comparison with which the variations in the electrical conductivity of the wires of the couple are negligible.

In use, the coil was perfectly dead-beat, and getting it into equilibrium, when a current was sent through it, took on an average two seconds.

Benedicks has already shown that such a lag does not deform the curves obtained with his apparatus, and this practically holds good with the present authors' galvanometer. They have every reason to assume that the accuracy of this recording arrangement greatly exceeds that with which the couple records variations of temperature in the sample, or in particular, the comparability of the laws of cooling, either in the same or in similar samples when repeating the same experiment.

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[1] The field being slightly affected by small variations in the voltage, due to the condition of the charge in the batteries (which varied more or less), it was necessary to make a correction in the measurements, as will be described later.

[2] A thin simple lens (a spectacle lens) of suitable focal length was placed in front of the mirror to allow of the formation of an image.

[3] The pole pieces employed were those shown to the right, below the magnet.

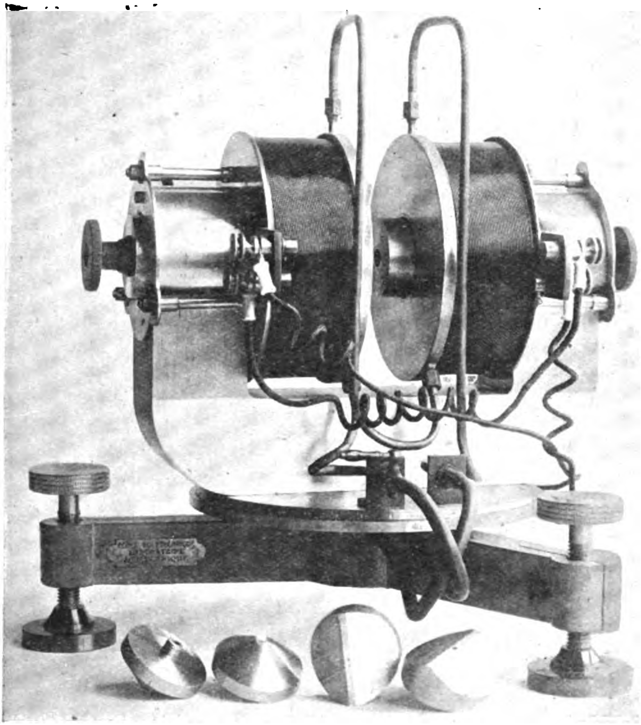

FIG. 6.—View of Galvanometer.

C. Description of the Experimental Arrangements.

The authors have stated, in the earlier part of the paper, the general considerations that guided them in the arrangement of their experimental appliances. The description of these arrangements will show how they have, given the resources at their disposal, applied these principles under the best possible conditions. As an entirely automatic apparatus, capable of being controlled by a single operator, was not available, the authors divided the functions of the two operators necessary, connection between them being effected by a convenient code of signals.

After some preliminary experiments carried out in the metallurgical laboratory of the École Centrale des Arts et Manufactures, with a simplified and perfectly inadequate set of appliances they had to continue their work at the École Polytechnique, where the authorities very kindly found room for them in the Mechanical Laboratory. The chief reason for this change in locality was that the continuous electric current available at the École Centrale fluctuated somewhat, and was, in particular, subject to sudden changes in voltage, which led to thickenings in the width of the curve, due to small periodic variations in the intensity of the field and to very annoying bends due to accidental variations. At the Polytechnic the authors were able to rely on a battery of accumulators of 110 to 115 volts, which furnished, out of the hours of charging and of work in the laboratories, a difference of potential sufficiently constant for their needs.

As already stated, the experimental appliances were arranged in two groups: (*a*) The apparatus for the heat treatment, and (*b*) the apparatus for checking and recording.

(*a*) *Arrangement of the Heat-treating Apparatus.*

Fig. 7 shows the apparatus, and Fig. 8, Plate XXVII., a diagrammatic sketch. A heavy base plate carries four uprights clamped together by a framework at their upper extremities. Within these uprights slides a platform, raised by a pulley worked by hand. This platform carries the furnace and the Meker blast-burner used for heating. The quenching apparatus is contained in a small vessel, which can be moved by slewing it round one of the uprights, so as to make room for the furnace. This vessel can be brought back into the axis of the whole apparatus when the furnace is lowered and slides vertically, being guided by two uprights. These manipulations are easily effected by means of a handle. Adjustable stops enable these different movements to be given the necessary range.

The quenching vessel can hold two interchangeable quenching baths. One of these for "sprinkling" consists of a rose cylinder 40 mms. in diameter and containing fifty 0·7 mm. holes, mounted on a screw of 8 mms. pitch. The water enters by an orifice made in the upper portion. This appliance can rotate within the vessel, which allows of its being moved backwards and forwards slightly, so as to render the cooling uniform. It was very seldom used during the experiments. (See Fig. 9, Plate XXVIII.)

The second appliance, for " immersion " (Fig. 10), was composed of a tube 35 mms. internal diameter, into which water arrives through a rose at the bottom (so arranged as to avoid the formation of a central jet), and empties itself by flowing over the upper rim. This apparatus was in almost constant use, and had a water supply of 2 litres per minute. (Plate XXVIII.)

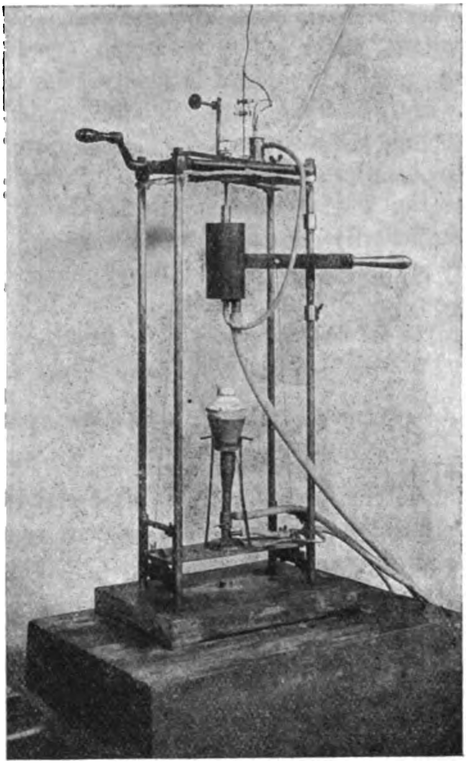

FIG. 7.—View of Quenching Apparatus.

A cross-piece attached to the upper frame supports the sample carrier and the thermo-electric appliance. The arrangement is shown on a large scale in Fig. 11, Plate XXIX.

The samples employed were in the form of turned cylinders, with plane ends at right angles to their axes, and three times the length of their diameters (Fig. 12). These cylinders were bored axially by a hole 2·5 mms. diameter, reaching to their centres and capable of being screwed by means of a thread of 4 mms. and 0·75 mm. pitch to the sample carrier,[1] which was of steel containing 0·4 per cent. of carbon and 30 per cent. of nickel,[2] through the axis of which passed the thermo-electric stem previously described. This stem can be raised by a steel wire clip attached thereto and by the help of a brass ring, through which passes a rack-and-

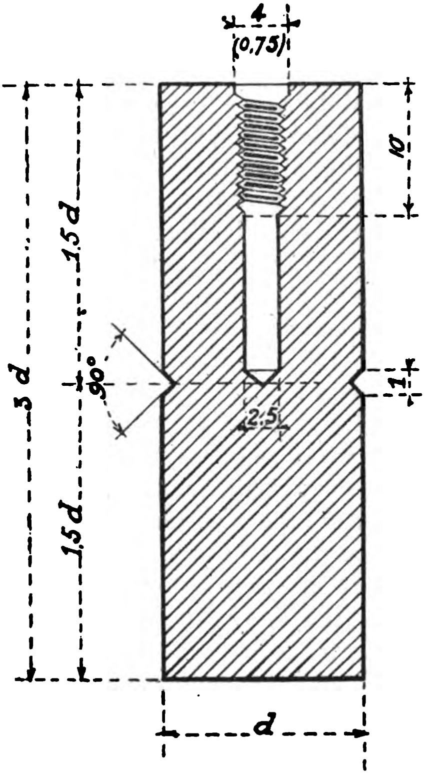

Fig. 12.—Cylindrical Sample.

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[1] A circular groove with a sharp angle, cut midway around the cylinder, allowed of the quenched samples being ultimately broken at right angles to their axes, at a plane coinciding with the conical point of the hole.

[2] This metal withstands successive heat treatments well, without much oxidation. Further, it does not undergo transformation at the temperatures reached by the samples in the authors' experiments.

pinion gear. This arrangement enables the stem to be raised until its extremity is entirely hidden within the sample carrier, which affords the possibility of screwing or unscrewing the samples and of cleaning the wires without risk of breaking the silica tubes. On the other hand, the stem remains absolutely free in the space containing it, and rests by its own weight on its extremity directly the latter touches the bottom of the cavity bored in the sample.

The wires of the couple were, so far as those portions not covered by the silica tubes are concerned, protected by means of crystal beads, and kept in position by two porcelain pulleys. Their ends were clipped together between the flattened and folded surfaces of two copper rods, and plunged in two of the tubes in the cold connection-box (Fig. 11, right hand), which consisted of a small cylindrical receiver furnished with two openings and closed by an ebonite disc kept in position by a screw-cap. This ebonite disc was bored with three holes to which were fitted, by means of india-rubber joints, three thin glass tubes, the bottoms of which were tightly corked. These tubes contained a little mercury. Two of them served to receive the ends of the couple, and of the wires connected with the recording chamber. The third held a mercury thermometer.

The water supplied to the quenching vessel flowed first through the connection-box, as shown in Figs. 7 and 8. The cold junction of the thermocouple was thus automatically kept at the same temperature as the quenching water, this temperature being read by means of the thermometer. The masses involved were small enough admirably to maintain equilibrium.

(b) *Arrangements for Checking and Recording.*

The apparatus was installed in a dark room, the concrete flooring of which rested on a solid arch, and was practically free from vibrations. The instruments were grouped on two benches, as shown in Fig. 13.

The checking bench, a bird's-eye view of which is shown in Figs. 14 and 15, Plates XXX. and XXXI., comprised:

A cut-off, on the main (current = 110 volts).

A double-break switch cutting the current off the electromagnet and that of the spot lamp.

A double-pole mercury reversing switch, allowing the current from the thermocouple to flow either to the dial galvanometer (which will be described later) or through the galvanometer coil to the electro-magnet.

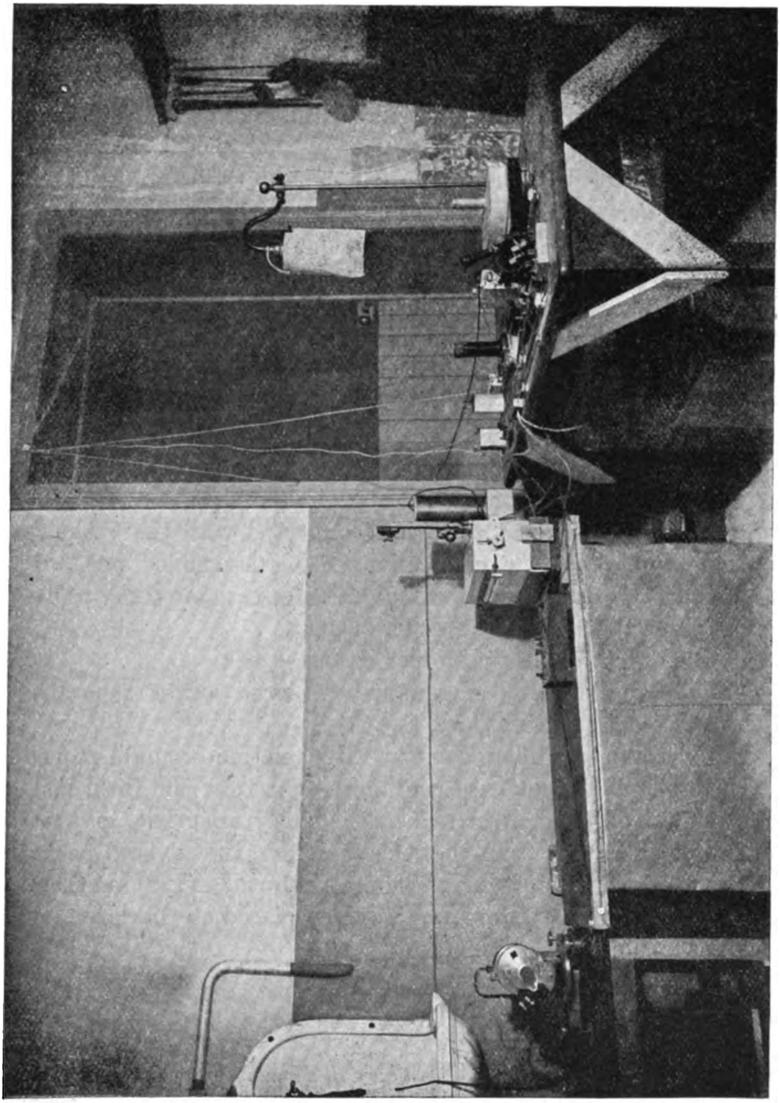

FIG. 13.—View of the Arrangements on the Recording Table and the Table of Connections.

A two-way switch shutting off the lamp which lighted the moving-coil galvanometer (which had the effect of throwing out of circuit the clock which served to make and break the spot reflections, the magnet which kept this clock out of equilibrium being in series with this lamp) and started the motor which drove the recording cylinder.

A lamp interpolated in the circuit of this motor, by changing which varying speeds can be obtained, is thus turned on. This lamp is on a level with the eyes of the operator who is about to quench, and serves as a signal to him that readings have begun to be taken.

A break switch interpolated in the circuit of an electric bell allows of various sound signals being given.[1]

A moving-coil galvanometer provided with a mirror and a sharp pointer, for ascertaining the temperature of the sample during heating.

A high-internal resistance battery (zinc + water containing a little zinc chloride + copper) and a switch forming the current control of the contact with the thermocouple.

From this bench went the wires connected with the various electrical appliances, the connections being assembled on two boards, so as to allow of rapid examination in case anything went wrong, which, by the way, never happened.

The recording apparatus proper consisted of:

The electro-magnetic galvanometer placed on a separate stand to avoid any vibrations.

The recording cylinder, covered with gelatino-bromide paper and enclosed in a stout case containing a narrow slit furnished with a shutter. The mirror, which is slightly prismatic, gives a double image, (1) that from the reflection from the silvered back, which serves for reading when the shutter is open, and (2) another, from the front surface, thrown on a screen placed on the case and serving as a check.

The electric motor driving the cylinder through multiple gearing and tangential screws.

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[1] The signal for quenching is given automatically by means of a friction pin carried on the axis of the recording cylinder and closing the circuit of the bell by contact with a little spring. This arrangement enables several curves to be plotted on the same paper, without any danger of superposition, by altering the angle of the stud each time. It also affords a means of regulating the time elapsing between the end of the heating and the quenching, during which the sample is cooling down.

The spot lamp[1] placed in a light tight box, with a window closed by a spring shutter pierced by a pin-hole. A rheostat served to regulate the intensity of this lamp according as the speed of the cylinder varied.

The pendulum intended to supply the factors for the time curve, composed of a small weight oscillating freely and capable of being drawn from its position of equilibrium by the attraction of a small electro-magnet, placed in series with the lamp lighting the checking bench. The pendulum rod carried two adjustments, one for the period of swing, which regulated the length of the pendulum spring, and one regulating the position of equilibrium and allowing the end of the pendulum, when at rest, to be brought into the plane cutting the light hole and the wire support of the frame. The latter regulator is necessary to obtain equispaced interruptions of the spot and to avoid the dashes forming the curve being alternatively long and short.

The diagrams, Figs. 14 and 15, show the two principal stages in the working of the appliances described above. Fig. 14 corresponds with the period of the heating of the sample, and Fig. 15 with the quenching and the tracing of the curve (Plates XXX. and XXXI.).

D. CONDUCT OF THE EXPERIMENTS.

In what follows the two operators are designated P and G respectively. P carried out the thermal treatment and G the recording, and looked after the connecting signals. They were also able to communicate with each other verbally, but only in predetermined phrases, articulate speech being exceedingly difficult across the screen that separated them.

1. *Preparation.*—P screwed the sample into its holder, lowered the couple, made the connection, and asked for "contact." G inserted, when required, the sensitive paper, put the cylinder and its stud in position, tested the contact and signalled one ring if the contact was good and two rings if it were defective. In the latter case P tested the apparatus and again asked for contact.

2. *Heating* (see Fig. 14).—P adjusted the furnace, regulated

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[1] The lamp employed contained a tungsten filament coiled into a spiral, the bulb being filled with nitrogen. This light has the advantage over arc lighting of being perfectly steady and is very photo-active, besides being bright enough. Its virtual diameter in relation to the hole was large enough for its image completely to cover the mirror, which obviated the necessity of employing a condensing lens which, in the circumstances, would absorb the actinic rays without, as is usually believed, increasing the intensity of the spot.

the gas and air and turned on the water-tap. G noted the temperature by means of the moving coil galvanometer. When it exceeded by a certain amount the quenching temperature, he tested the contact and rang the bell. P thereupon turned off the burner. G took note of the slow cooling of the sample. As the sample reached the desired temperature, he turned the switches and brakes from right to left and opened the slit in the cylinder case.

3. *Quenching* (see Fig. 15).—P being warned by the lighting up of the lamp constituting the motor resistance, that the recording cylinder had started, lowered the furnace and swung on the quenching vessel. On the stroke of the bell, given automatically by the contact stud, P rapidly raised the vessel and fixed it in position for quenching.

4. *End of Experiment.*—When the recording cylinder had made a predetermined fraction of a revolution—that is to say, at the end of a certain time of quenching sufficient to cool the specimen—G closed the slit of the recording cylinder and changed over the switches from left to right, thus restoring them to their original position, and tested the contact.[1] P, warned by the extinction of the lamp, lowered the quenching vessel, raised the thermocouple, and unscrewed the sample. He then proceeded to clean the threads, which he freed, by means of a little brush, from the dust arising from the heating and the quenching, and then replaced the furnace. The heat from the sides of the latter sufficed to dispel the traces of moisture resulting from the condensation of the water vapour which sometimes occurred in the apparatus.[2]

P then asked "Dry?" to which G replied by a single ring as soon as the needle galvanometer indicated about 150°.

The operations could then be repeated for the next experiment. At the end of the series, G gave the cylinder a turn, the galvanometer stand being short circuited and the pendulum break switch kept at a deviation, so as to trace a zero line. There was nothing more to do than to note (as was done at the beginning and end of each series of experiments) the temperature of the quenching water, the voltage of the battery supplying the electromagnet, and to develop the curves.

Remarks.—As may be seen from the foregoing, the authors applied themselves as far as possible to attaining automatism, so far as the necessary movements of the operators were concerned.

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[1] The contact had to be as perfect after as before the quenching, otherwise the result of the experiment was deemed doubtful.

[2] The drops of water thus formed in the thin quartz tubes, on suddenly evaporating during the heating of the next sample, would have led to a risk of breaking the couple.

This mode of working presents numerous advantages, which are chiefly:

1. The best mode of avoiding errors and accidents which would necessitate the experiments being recommenced.

2. The reduction to a minimum of the influence of the personal equation of the operators.

3. The shortening of the experiments by doing away with all groping and uncertainty. The latter consideration appealed to them very greatly as, for several reasons, they could only devote a very short time each day to the experiments. Be this as it may, they are, however, convinced that it is of great advantage, in any investigations involving a long series of similar experiments, to systematise the latter. The time spent for this purpose in perfecting the experimental apparatus is to a large extent recouped, the more so as much of the work can, in many cases, be deputed to careful assistants, when these are available.

E. EXAMINATION OF THE EXPERIMENTAL RESULTS.

The curves obtained assumed the form shown in facsimile in this paper. Each dash corresponds with a time interval of 0·4 second, except in certain curves where the pendulum was replaced by a clockwork movement giving interruptions every five or ten seconds.

The horizontal lines to which the curves are asymptotic correspond with the final temperature of the sample at the end of a considerable interval, that is to say, with the temperature of the running water used for quenching,[1] that is, practically, the line corresponding with no current in the coil (the temperatures of the junctions being equal).

The curves yield, to begin with, a certain amount of information as to the kind of phenomena, particularly as to the transformation points at high temperatures. However, their complete interpretation cannot be effected without a preliminary transposition, owing to:

1. Variations in the scales of the abscissæ (times), owing to the rate of the motor not having been absolutely constant.

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[1] This temperature differed but little (6° to 10°) during the course of the experiments.

2. Variations in the scales of the ordinates (temperatures) corresponding with variations in the voltage of the current supplying the electro-magnet.

3. The non-proportionality of the latter scale.

It was therefore necessary to replot the curves by points, which could be done with considerable accuracy, thanks to the time readings, by means of a temperature scale. The latter was drawn up as follows:

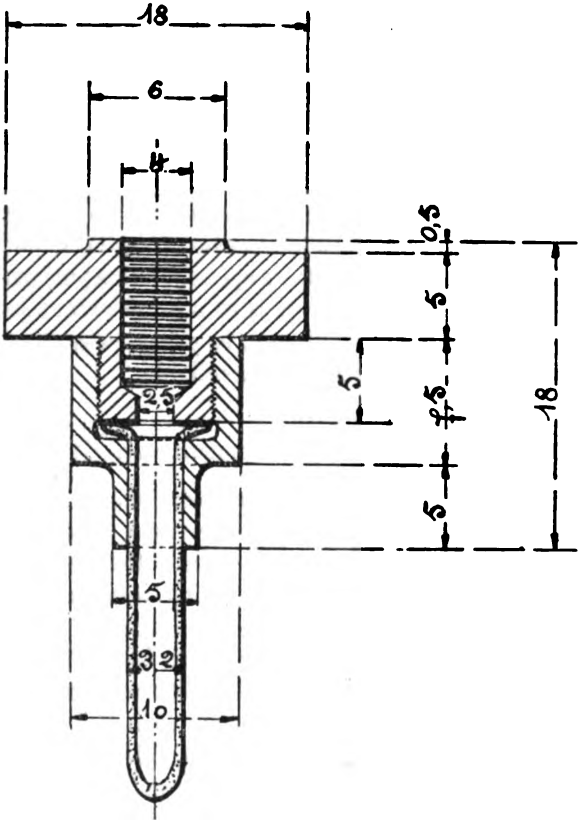

FIG. 16.—Protective Cover for Standardisation.

There was rigged up on the sample carrier the silica tube thermocouple protector, shown in Fig. 16, and there was placed on a triangle fitted into the furnace, the cover of which was removed, a small crucible filled with some pure metal (tin or antimony).

The silica tube was plunged into the metal (which was previously melted) by raising the furnace, and the thermocouple was lowered into the tube.

The crucible being then allowed to cool down, the cooling curve of the metal was recorded. These curves are represented by Fig. 17. The rise of the temperature, due to superfusion, is clearly seen, even in the case of tin. The irregularities have been regarded as corresponding with the temperatures 232° and 631°; the horizontal line (current = zero) relates to the temperature of the water, which circulates through the junction box during the operation.

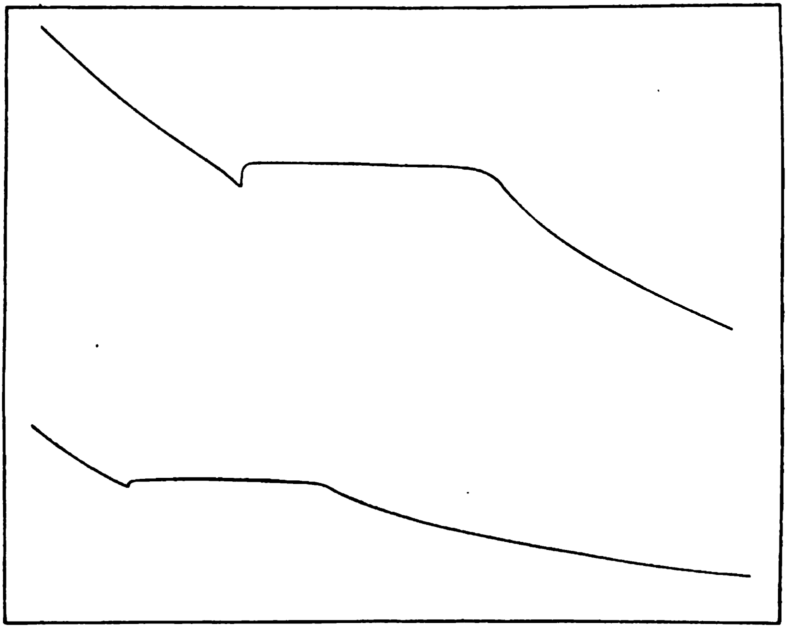

FIG. 17.—Standardisation Curves—Solidification of Antimony and of Tin.

On the other hand, the formula given by Holborn and Day (1910), and stated by them to apply to $t > 250°$, namely,

$$E = -0{\cdot}310 + 0{\cdot}00805t + 0{\cdot}00000172t^2$$

has been employed by the authors in calculating the electromotive forces (millivolts) given by the couples platinum-platinum-rhodium, to which this formula applies for the temperature differences *t* between the junctions within the range 232° to 1000°. The result of this calculation is given below:

t°.	E.	t°.	E.
232	1·65	631	5·455
250	1·81	700	6·17
300	2·26	800	7·23
400	3·185	900	8·35
600	5·14	1000	9·46

The curve thus calculated has been collated with the original by taking it through the points:

$$t = 100,\ \mathrm{E} = 0{\cdot}67\,;\ t = 200,\ \mathrm{E} = 1{\cdot}41.$$

By means of the above values the authors have plotted a divergent graph giving proportional scales, on which have been plotted the ordinates corresponding with the perturbations in the calibration curves. This method gives a satisfactory agreement, the three points—temperature of the water, melting point of tin, melting point of antimony—ranging themselves practically at the intersection of the same parallel to the right, carrying the scale calculated, and the lines joining the point of focus of the points corresponding with the latter scale.

This gives the scale of the temperatures corresponding with a given voltage of the battery supplying current for the electromagnet. It remains to ascertain the relative correction for variations in that voltage. For this purpose three successive records were taken of the solidification curve of antimony—one with the battery furnished with its normal number of elements, one with two extra elements, and one with two elements fewer. The voltage was thus made to vary to the extent of about ± 4 volts of its average, which included the variations due to the state of the charge. A variation of 1 volt corresponded practically with a variation of 0·6 per cent. of the temperature scale.

This gives all the factors to draw up scales corresponding with each value of voltage (from volt to volt) used in plotting the curves. It was thus possible to draw up tables giving the temperatures at the centre of the sample corresponding with time intervals varying in arithmetical progression (generally from 0·4 second by 0·4 second). These curves were replotted with proportional ordinates and abscissæ, and those which related to a repeat of the same experiment could be superimposed. This superposition was generally very satisfactory, as the example in Fig. 18 shows, where the drawing shows the points corresponding with two superimposed curves.

In order best to summarise the results, several figures of curves have been plotted (Figs. 19 to 23). In these figures the convex portions of the curves corresponding with the commencement of quenching have been omitted, and all the curves have been correlated to one and the same point (usually corresponding with the temperature of 700°). In some (Fig. 22) the temperature of quenching being below 700° extrapolated portions of the curves have been carried up through the point in question, but only actually existing portions of the curves are shown.

In curves exhibiting anomalies intermediate points have been plotted in order to ensure as correct a representation as possible.

Finally, facsimiles of some of the curves have been given in cases where only the nature of the phenomena was of interest. The time graduations are given by the interruptions.

Accuracy of the Measurements.—The curves corresponding with samples which, owing to their nature or dimensions, cool more slowly should represent, with considerable accuracy, the phenomena accompanying the cooling. The errors should not exceed 1 per cent. of the temperatures.

With small samples of metal cooling rapidly the agreement is sometimes bad, but this may, in the authors' opinion, arise from the preponderating influence, in such samples, of local and accidental causes affecting the surface conditions. These causes have practically no influence in the case of a quenching lasting some time, owing to the compensation which seldom fails to occur. Such errors as are involved extend proportionally to the temperature scale, as it figures in the authors' curves. It is possible that the departures from the normal thermometric scale (the gas thermometer) may be somewhat magnified, a matter which is not, however, one of much importance.

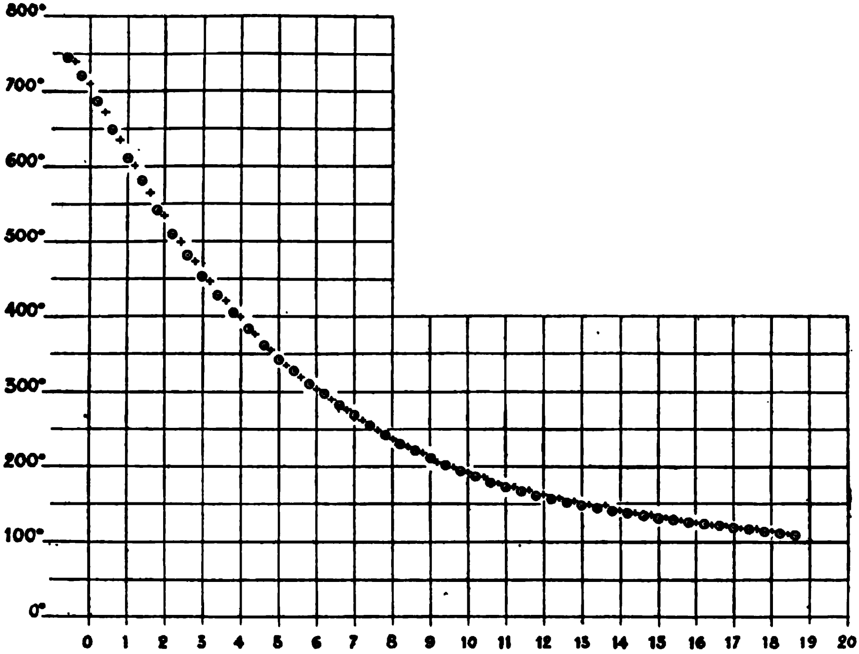

FIG. 18.—Superposition of Two Curves.

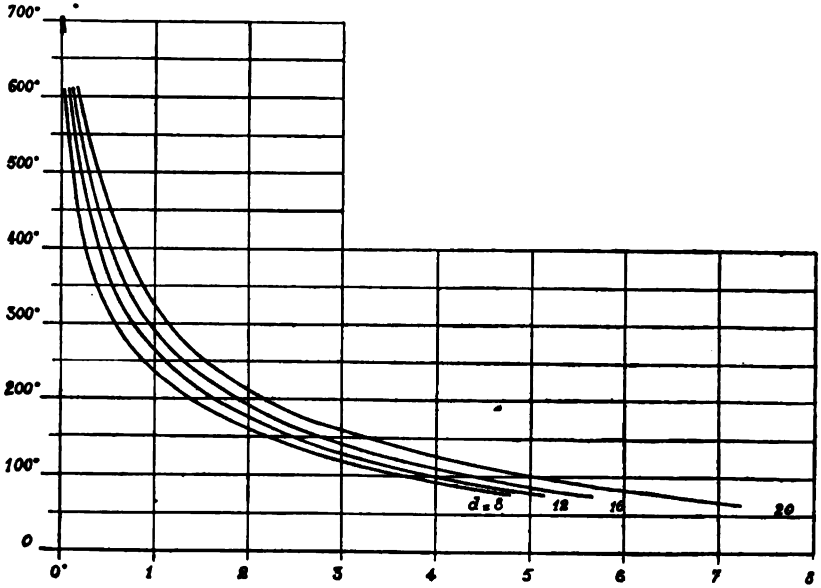

FIG. 19.—Experimental Curves for Silver.

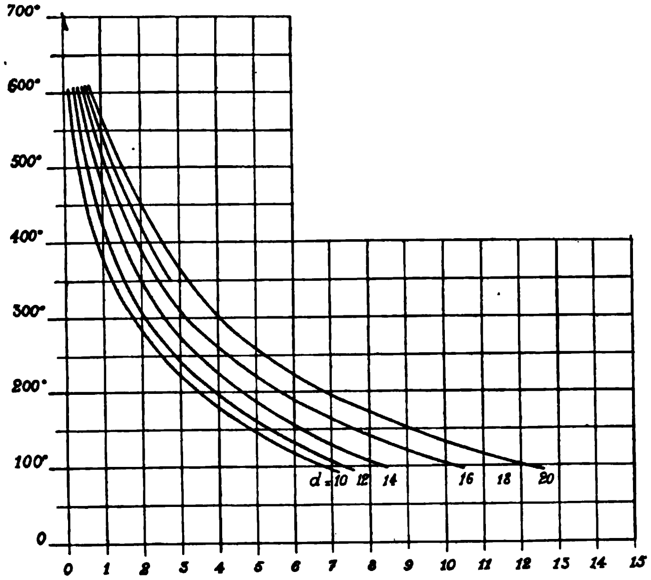

FIG. 20.—Experimental Curves for Nickel.

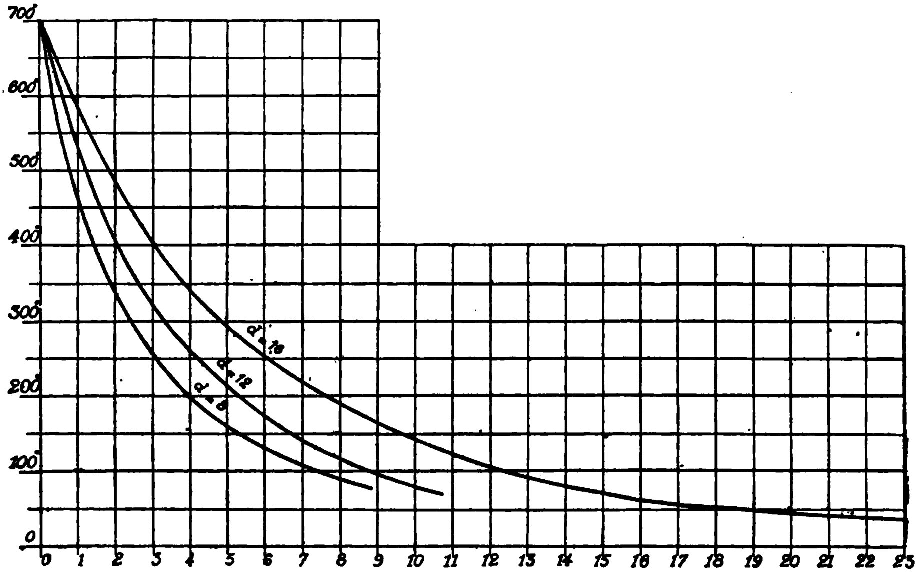

FIG. 21.—Experimental Curves for Ferro-nickel.

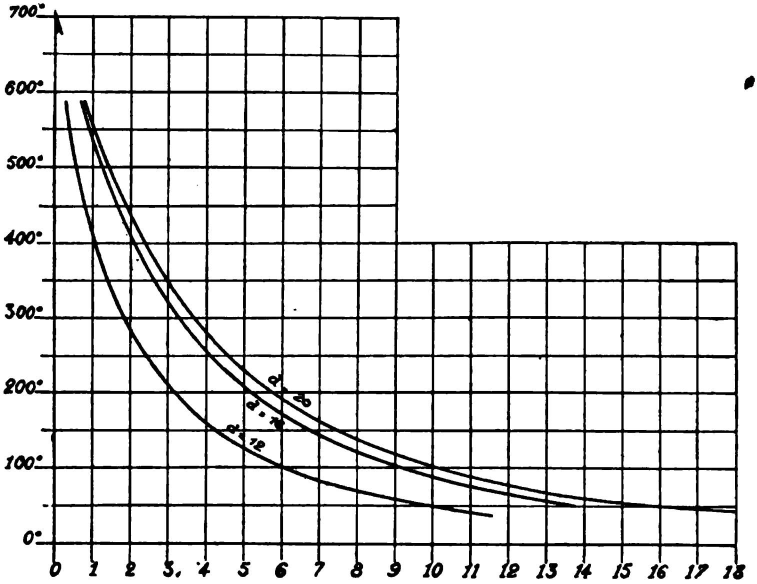

FIG. 22.—Experimental Curves for Eutectic Steel quenched at 630°.

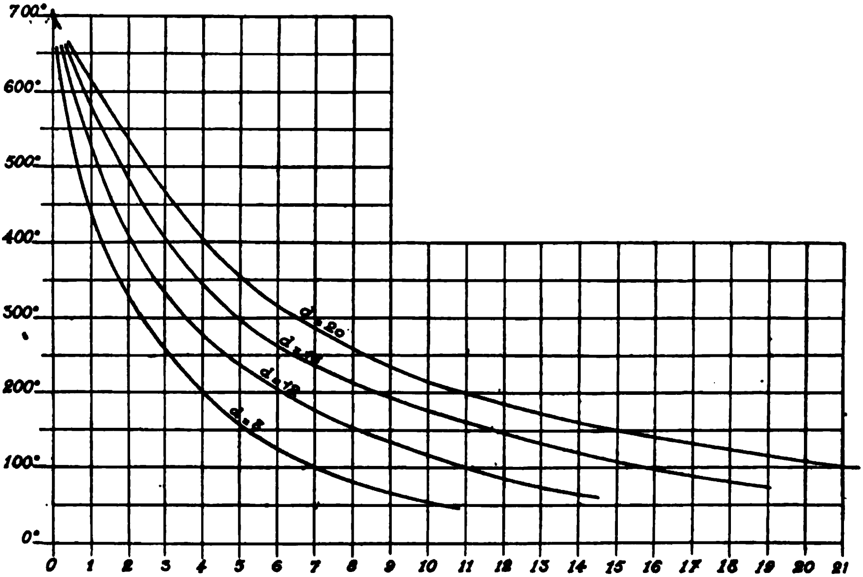

FIG. 23.—Experimental Curves for Eutectic Steel quenched at 760°.

F. CONCLUSIONS TO BE DRAWN FROM THE FOREGOING RESULTS.

The authors endeavoured to ascertain whether, as Mr. McCance had suggested,[1] the results obtained could be expressed with sufficient accuracy by a mathematical formula containing a single parametric function of the dimensions [2] and those of the physical properties of the sample.[3] If this were so, the temperature θ at the instant t for a given quenching temperature would take the form

$$\theta = F\left(\frac{t}{\lambda}\right)$$

λ being the parameter in question. If, then, $T = \frac{t}{\lambda}$ be taken as the variable, all the cooling curves will have, as an equation, $\theta = F(T)$, and will therefore be superposable.

In other words, the curves corresponding with the quenching of different samples under identical conditions should differ only in the scale of their abscissæ.

Unfortunately, this hypothesis does not agree with the facts, and is only appreciably true in regard to samples having much the same diameters when of the same metal, or possessing somewhat similar physical properties if they are of different metals.

The authors have indeed plotted the set of curves represented in Figs. 24 and 25, and deduced therefrom, by a variation in the scale, the abscissæ of quenching curves at 750°/10°, corresponding with a sample ($d = 16$) in steel containing 4·30 per cent. of nickel and in a sample of nickel ($d = 20$)—that is to say, samples cooling at a relatively slow rate. If the attempt be made to superpose these curves on the experimental curves corresponding with samples cooling at a rate appreciably greater than those referred to, it is found that the former fall more rapidly than the latter at low temperatures, whereas the gradient at the commencement of the cooling is the same. If a set of curves (Fig. 26) be plotted—

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[1] *Journal of the Iron and Steel Institute*, 1914, No. I. p. 192.

[2] Given the shape adopted for the authors' samples, their dimensions are wholly determined by the value of the diameter d. This diameter, which varies between 8 mms. and 20 mms., is given in each case, as is also the nature of the metal.

[3] Which is assumed to be transformable within the temperatures traversed.

corresponding, for example, with a quenching at 750°/0°—of samples having different parameters, λ, according to the formula given by Mr. McCance,[1] the superposition becomes worse than

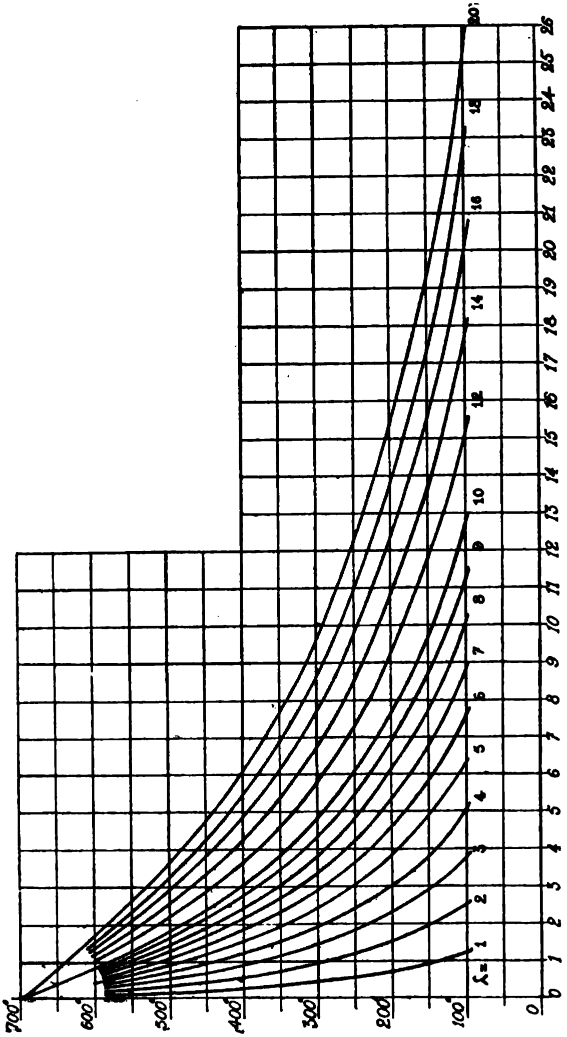

FIG. 24.—Theoretically derived Curves for Ferro-nickel Cylinders of 16 mm. in Diameter.

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[1] This calculation was made by means of the formula:

$$\theta = 750 \left[1{\cdot}603 \times 10^{-\frac{t}{\lambda}} - 1{\cdot}065 \times 10^{-527\frac{t}{\lambda}} + 0{\cdot}853 \times 10^{-12{\cdot}93\frac{t}{\lambda}} - 0{\cdot}732 \times 10^{-24{\cdot}07\frac{t}{\lambda}} \right]$$

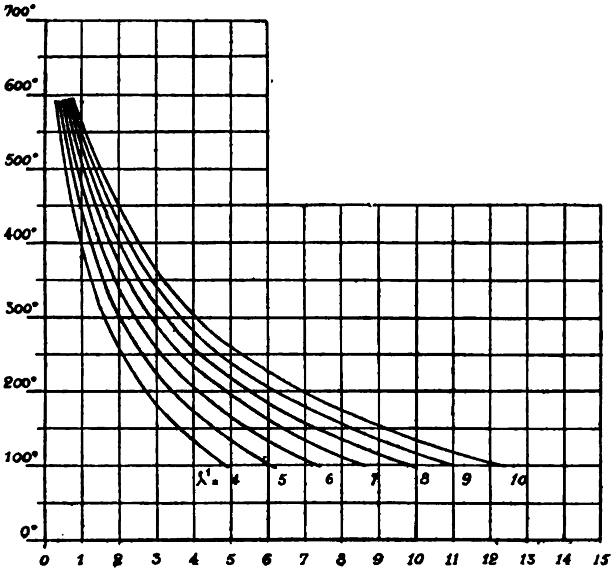

FIG. 25.—Theoretically derived Curves for Nickel Cylinders of 20 mm. in Diameter.

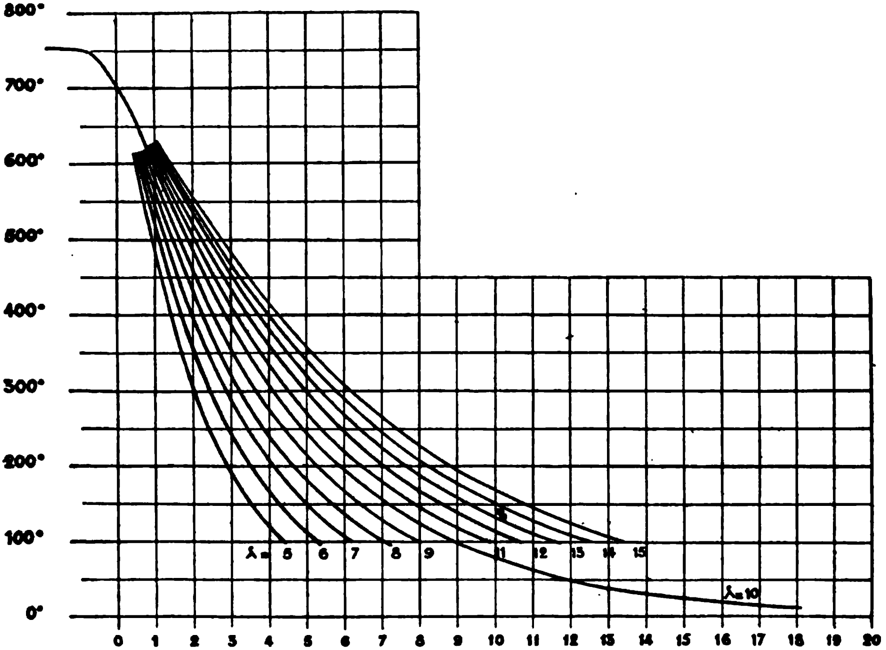

FIG. 26.—Derived Curves plotted by McCance's Formula.

ever. This result is not really surprising: Fourier's theory assumes, indeed:

(*a*) That the physical properties of bodies do not change appreciably within the temperature interval in question, and

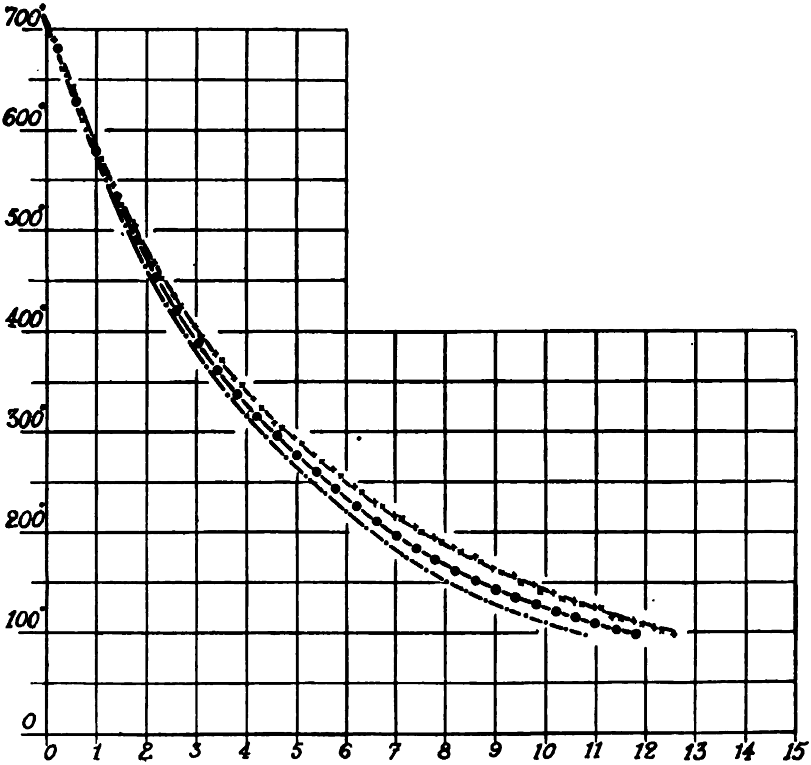

FIG. 27.—Influence of the Quenching Temperature on the Cooling of Ferro-nickel.

(*b*) That the cooling fluid maintains a more or less uniform temperature,

conditions that only apply in the case of quenchings at 700° or 800°.

If, therefore, it is intended to study (as will be done later) the influence of the liberations of internal heat arising from transformations in the metal of the sample, on the law of cooling, there must be taken, as a basis of comparison, samples of a metal which is not transformable at the temperature traversed, and such that, given the same diameter, the rate of cooling is in the neighbourhood of that of the sample metal.

To revert to the authors' curves relating to non-transformable

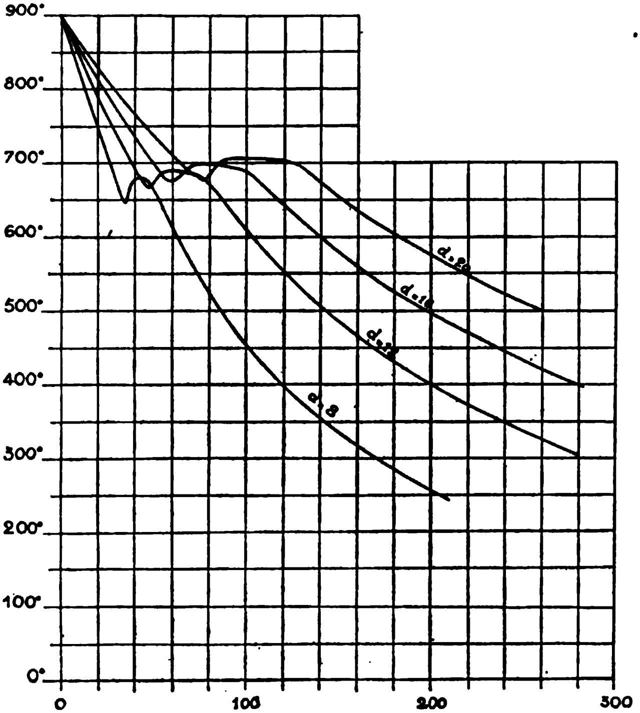

Fig. 28.—Curves of Air cooling at the Centres of Cylinders of different Diameters, starting from 900° in a Steel approaching Eutectic Composition (carbon, 1·07 per cent). Progressive lowering of the Recalescence Temperature (Ar3,2,1).

metals, Fig. 27 shows that, as already pointed out by Professor Le Chatelier, the rate of cooling increases with the temperature of quenching.

It was, on the other hand, of interest to ascertain the influence of the dimensions of the sample on the average rate of cooling, between two given temperatures. The authors therefore plotted the graphs (Fig. 28) by taking as the abscissæ the diameters of the samples, and as ordinates, the period of cooling between two temperatures (shown on the graph). For samples of very pure metals of high conductivity the points obtained are practically along a straight line, and do not pass through the point of origin. For alloys, or pure but badly conducting metals, the points are more or less in line with the starting-point.

PART II.

THE EXPERIMENTAL INVESTIGATION OF THE QUENCHING OF CARBON STEEL.

I. Introduction and Enunciation of the Problem.

The result of the operation of quenching, which consists essentially of the more or less rapid cooling of the steel from a temperature T, which we will call the temperature of the commencement of the quenching, depends upon two given conditions:

(1) A complete definition of the state of the metal at the commencement of quenching—that is to say, at temperature T.
(2) The law of cooling.

The authors are for the present concerned solely with the question of the law of cooling, although it is necessary to bear in mind what is implied in the knowledge of the state of the metal at the temperature T. They will have to revert to this point in their final conclusions on the research.

This state depends, as a matter of fact, on the chemical composition and on the history of the previous heat treatment of the steel. It can therefore be known when the following factors have been stated:

(*a*) The complete chemical composition.
(*b*) The initial state of the metal—that is to say, its internal condition at the commencement of the heating which precedes the quenching
(*c*) The law of heating according to which the metal has been brought from the surrounding temperature to the temperature, T, of the commencement of quenching, and notably the maximum temperature attained.

during the heating, and the period at which it has remained at that temperature.[1]

In the experiments to be described subsequently the starting-point has always been, in the case of each steel studied, the same initial state. Also, the term "a given steel" will imply, in the sequel, a constant chemical composition and initial state. Further, every attempt has been made to render the heating conditions for all samples of the same size identical, and to render them similar in geometrically similar pieces. These conditions of heating have been described in the account given in the first part of this paper, of the experimental arrangements.

Law of Cooling.—The law of cooling depends, for a given steel, on the following factors: [2]

(*a*) Temperature at the commencement of quenching, or initial quenching temperature.

(*b*) Mass, form, and dimensions of sample.

(*c*) Position of a given point in the interior of the sample.

(*d*) Nature of the bath—that is to say, of the medium in which quenching takes place—which acts according to its physical properties, particularly its specific heat, its latent heat of vaporisation, its conductivity, and its viscosity.

(*e*) The temperature of the bath, which may vary during the process of cooling, according to the respective masses of the bath and of the sample.

(*f*) Agitation of the bath in relation to the sample.

(*g*) State of the surface of the sample.

(*h*) Temperature at the end of the cooling, or final quenching temperature, or emersion temperature.

This law of cooling is, for a given point within the sample, absolutely defined by its representative curve $t = f(z)$, giving the variation of the temperature t in terms of the time z.

For the laws of similar cooling it would be sufficiently defined by the average rate of cooling between two given temperatures or by its reciprocal—that is to say, by the time necessary to traverse a given temperature interval.

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[1] See Portevin, "Influence of the Time of Heating before Quenching on the Results of that Operation," *Bulletin of the Société d'Encouragement*, 1914, vol. cxxi. p. 207; and *Revue de Métallurgie*, 1916, vol. xiii. p. 9.

[2] See, for further information on this subject, the works of Osmond and of H. Le Chatelier.

The authors have adopted as a symbol of the rate of cooling the time which elapses during the passage from 700° to 200°, which is designated by τ (700°–200°), or by the symbol τ alone.

In earlier researches on the rates of quenching investigators chose, for this purpose, the temperatures 700° and 100°. The authors have selected a temperature 100° higher than the latter because, having extended the experiments to samples of larger mass, the gradient of the curve, on the uniform scale adopted for all the samples, became very small, particularly when there was a liberation of heat at a low temperature, of which mention will be made later. Very little inaccuracy is thus introduced in the graphic determination of the abscissæ corresponding with the ordinate 100°.

Given the foregoing, two problems arise:

1. How does the law of cooling, or the value of τ vary with the value of the factors enumerated in (*a*) to (*h*) above?
2. What relation exists between τ and the final state of a given steel and a given initial cooling temperature, this final state being determined by the hardness and the micrographical appearance?

It is the first of these two problems which has hitherto engaged the attention of experimenters. The researches of H. Le Chatelier,[1] followed by those of Lejeune [2] and Benedicks,[3] have investigated and thrown light on the influence of the factors enumerated above, on the law of cooling and on the value of τ. At present enough information has been acquired on this subject to allow of the law of cooling of any sample submitted to quenching being varied as desired and in any direction sought. This is, however, only a means—what is wanted, in the quenching operation, is to give the metal the qualities it is desired it should possess, which depend on the state attained to by quenching. In other words, it is necessary to know the relation between τ, a value variable within certain limits, at will, and the properties of the quenched metal. These properties are characterised, as has been already said, by hardness.

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[1] *Revue de Métallurgie*, 1904, vol. i. p. 473.

[2] *Ibid.*, 1905, vol. ii. p. 299.

[3] *Ibid.*, 1909, vol. vi. pp. 182 and 852.

It is therefore the second problem which is under investigation here, the investigation of the relation which exists between τ the microstructure and the hardness after quenching—or in other words, the influence of the rate of quenching on the state after quenching.

This state after quenching is the direct and immediate consequence of the transformations which take place in the course of cooling; we are thus naturally led to investigate the effect of the rate of cooling on the mode in which these transformations take place, and this, as already stated, will depend on the initial state at quenching—that is to say, the temperature at the commencement of quenching and the initial state of the metal, so that the problem can be accurately stated in the following terms:

In a given steel, how will (1) the transformations in the course of the cooling during quenching, and (2) the structure and hardness of the steel after quenching, vary, in terms of the rate of cooling, indicated by τ, and of the initial temperature on quenching?

Reciprocally, we shall be led to revert, incidentally, to the former problem, by showing the reaction, on the law of cooling and on the duration of the quenching τ, of the mode of occurrence of the transformations during the quenching, and of the dimensions of the sample.

The problem thus stated has been experimentally dealt with in regard to chromium steels by Messrs. Greenwood and Kikkawa,[1] and for nickel-chromium steels by Masloff,[2] and for the latter steels, collectively, by one of the present authors.[3]

These investigations, however, relate to steels in which the hardening by quenching takes place at relatively slow rates of cooling, obtained in the air, and in the course of easily observable phenomena. In the present instance the authors dealt almost entirely with carbon steels, in regard to which hardening by quenching takes place only by immersion in water—that is to say, for total periods of cooling which are incomparably shorter.

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[1] *Journal of the Iron and Steel Institute*, 1914, No. I. p. 508; 1916, No. I. p. 114.

[2] *Revue de la Société Métallurgique Russe*, 1916, vol. i. p. 495.

[3] Portevin, *Revue de Métallurgie*, 1917, p. 707.

II. EXPERIMENTAL CONDITIONS.

The experimental arrangements have been fully described in the first part of this memoir, to which reference should be made for all details. As before, the samples used were always geometrically similar, and consisted of cylinders whose length was three times their diameter, and the law of cooling of the centres of which was studied. After quenching, the samples were broken in half, without appreciable deformation, by means of the little groove cut around them midway, and after polishing the surface at right angles to the axis, and cutting the cylinder along the plane of the bottom of the hole, it was possible to study the exact spot within the metal which had been in contact with the junction of the thermocouple, that is, the point, the cooling curve of which had been recorded.

Further, the examination of the whole of this section furnished information as to the depth of the hardening, the geometrical conditions $h = 3d$ being more than sufficient to eliminate any perturbatory influence due to the cooling of the ends of the cylinder.

Benedicks' experiments afford interesting information in regard to the necessary degree of accuracy to be attained in the measurements.

Durations of Cooling.—The durations of cooling, τ, are only actually known within 0·2 second, more or less, for, as Benedicks says in his study of cooling, " Although the instrument used was capable of working to the second decimal, still even the first decimal of any one τ determination cannot be guaranteed."

In addition, the present authors give below the results of two of Benedicks' experiments, which are in this connection particularly suggestive :

No.	Per Cent. C in the Steel.	Dimensions of Sample.		Time of Heating. (Mins.)	Temperature of Quenching. t°.	Temperature of Water. t°.	τ 700°–100° Seconds.
		Length. Mm.	Diameter. Mm.				
B 8	1·33	50	6·2	12	849	13·0	6·42
B 9	1·33	50	6·2	12	848	13·5	5·67

Thus, with conditions of quenching which should be considered as strictly identical, τ varies 0·75 second from one experiment to another. The authors have not had such differences in their repeat experiments, even when the quenching temperatures have varied by 20°.

Temperatures of Quenching.—The accuracy of the temperature measurements in quenching does not need, therefore, to be so great. In the authors' experiments they are comparable within about 5° in the same series of experiments, which, as will be seen, is quite sufficient to guard the conclusions arrived at from any criticism on this account.

Besides this, the influence of the initial temperature of quenching on the duration of the cooling, an influence which is clearly brought out in the first part of this paper (see Fig. 27), appears to be neither very important nor particularly noted in Benedicks' experiments. The figures he quotes in support of his conclusions are as follows:

Temperature of Quenching.	Duration of Quenching from 700° to 100°.
950	3·07
845	4·43
750	4·11

A rise of temperature of 100° gives by experiment a diminution of 0·32 second, and an increase of 1·35 second. Here, again, the inevitable experimental errors are of a higher order than those of the measuring instruments.

Dimensions of the Samples.—Except in the case of one experiment, all Benedicks' tests were carried out on samples having a diameter below 8 mms. His important work is remarkably complete, and it is useless again to traverse a field so well explored. On the other hand, the authors wished to work with average rates of cooling varying within much wider limits, and the diameters selected range from 8 mms. and 20 mms.

Chemical Composition of Steels Studied.—The steels were all crucible steels, and the results of their chemical analyses are given in Table I. below. Each steel is designated by a letter (*a* to *i*).

Other Experimental Conditions.—It results from H. Le Chatelier and Benedicks' experiments that the duration of the heating, the temperature of the quenching water, and the rate of the agitation of the water in relation to the sample will exert only a negligible influence on the rate of cooling. This notwithstanding it will be seen, from the description of the authors' experimental arrangements, that these factors were maintained as constant and as comparable as possible. The temperature of the water was nearly always 10° ± 2°. In exceptional cases it fell to 5°.

TABLE I.—*Analysis of the Steels Investigated.*

Description of the Steel.	C.	Mn.	Si.	S.	P.
a	0·10	0·42	0·06	0·027	0·010
b	0·19	0·15	0·01	0·027	0·011
c	0·33	0·19	0·19	0·027	0·014
d	0·50	0·13	0·09	0·019	0·015 traces of nickel
e	0·56	0·26	0·28	0·043	0·019
f	0·81	0·21	0·38	0·018	0·020
g	1·07	0·08	0·29	0·019	0·030
h	1·10	0·40	0·48	0·032	0·017
i	1·45	0·20	0·17	0·037	0·014

III. THE LOWERING OF THE TRANSFORMATION POINT.

From Osmond's researches we know that the transformation points are lowered when the rate of cooling is increased, which is likewise a general fact as regards all equilibrium reactions.

Take, for example, a steel in the neighbourhood of the eutectic (steel *f* or *g*, Table I.), and let cylinders of decreasing diameters be cooled in air, starting from the same temperature of 900°, so as to obtain increasingly rapid rates of cooling. It will be found, as is shown in the curves in Fig. 28, that the recalescence point Ar3,2,1 becomes gradually lowered. The rate of this lowering may be expressed thus:

Diameter of Cylinder. Mms.	Period required to traverse the Interval.		Temperatures	
	900°–700° Seconds.	800°–500° Seconds.	at the Beginning of the Recalescence. Degrees.	at the Maximum of the Recalescence Ar3,2,1. Degrees.
20	73	31	686	707
16	56	25	685	700
12	40	18	670	690
8	24	13	650	680

It may be noted, incidentally, that the times required for the temperatures of the samples to fall 100°, outside the transformation range, are practically proportional to the diameters of cylinders geometrically similar. In these circumstances the transformation temperature Ar3,2,1 becomes gradually lowered in proportion as the average rate of cooling increases, but care should be taken not to regard this phenomenon as subject to extrapolation, for, as will be seen later, when water quenching is involved—that is to say, rates of cooling at which the temperature interval 600° – 500° can be traversed in time periods of the order of one second—it will be found that the transformation point is no longer visible at a high temperature on the curves (steel *f*), or still subsists towards 650° (steel *g*). This leads us to foreshadow a discontinuity in the law of the lowering of the transformation point, or at least a variation in this lowering which is

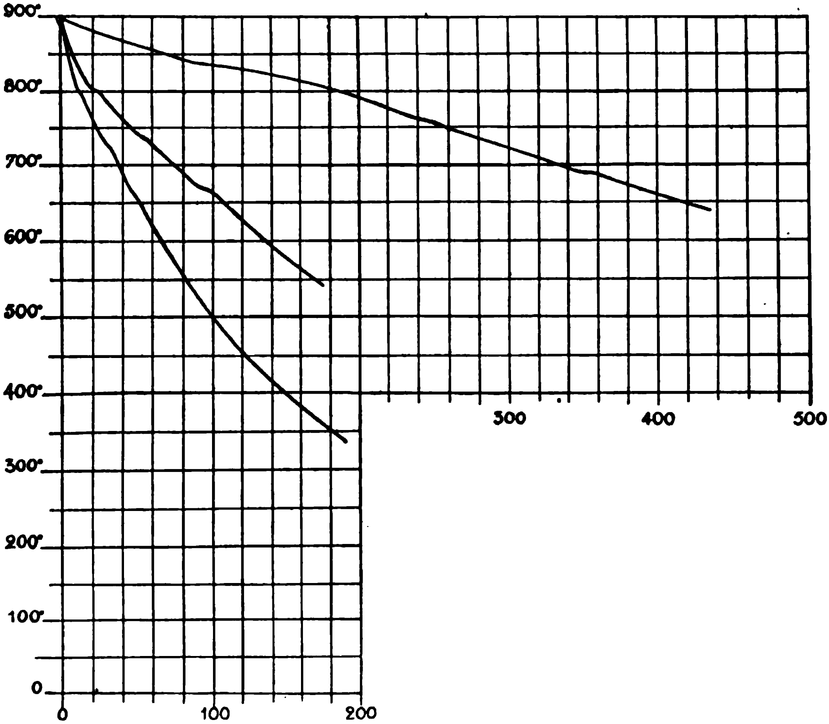

FIG. 29.—Curves of Air cooling at the Centres of different Soft Steel Cylinders (carbon, 0·10 per cent.), starting from 900°.

not a gradual one, which brings us to the conception of what we call the "critical speeds of quenching."

Figs. 29 and 30 bring out the phenomena of the lowering of the transformation point for steels with a lower carbon content (Fig. 29, steel *a*, with 0·10 per cent. of carbon; Fig. 30, steel *b*, with 0·19 per cent. of carbon). The variations in the rates of cooling were, in these instances, obtained by acting both on the diameters of the cylinders and on the external conditions (cooling in air, or in the warm oven).

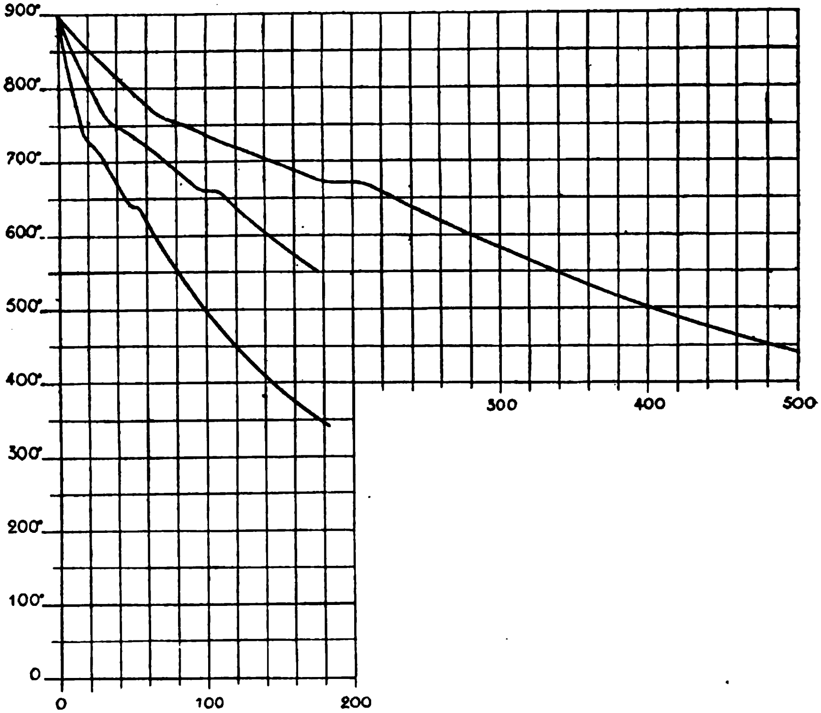

FIG. 30.—Curves of Air cooling at the Centres of Mild Steel Cylinders (carbon, 0·19 per cent.), starting from 900°.

There is a simultaneous lowering of two points Ar3,2 and Ar1 (Fig. 29), or of the three points Ar3, Ar2, Ar1 (Fig. 30) in the curves. This lowering is, between the first and the third curve in each figure, about 30°.

Setting aside mild and dead soft steels for which the abnormalities of the curves rapidly become imperceptible as the rates of cooling increase, the authors will now deal with very rapid coolings—that is to say, with quenching properly so called. What is important to remember is the continuity in the lowering of the transformation point on cooling,[1] so long as this point is above 600°, which shows that, in this case, the phenomenon involved is always the same.

IV. Conception of the Critical Rates of Cooling.

The Formation of Troostite and of Martensite.

In order that the phenomena about to be described shall be thoroughly understood, the authors will begin by explaining a series of examples, thus following the course adopted in their experiments, and enunciating, step by step, the views and the conclusions to which they gave rise.

1. *The Hypereutectic Steel* g, *with* 1·07 *per Cent. of Carbon and* 0·08 *per Cent. of Manganese, Quenched at about* 750°.

This first series of experiments was the most complete, inasmuch as, in order to restrict the examination of the phenomena, the authors selected for study the cooling of cylinders, the diameters of which varied by 2 mms. and sometimes by 1 mm. In Fig. 31 there have been reproduced the typical curves ascertained for the centres of the samples, and in the table below are given the average corresponding characteristics :

Diameters of the Samples.	No. of the Curve in Fig. 31.	τ 700°–200°.	Temperature of the Abnormality distinctly Visible in the Curve.	Micrographic Appearance. Chief Constituent.[2]
Mms.		Seconds.	Degrees.	
8	1	4·4	...	M
10	2	5·5	...	M
12	3	6·2	...	M
13	4	6·6	...	M
14	5	6·9	635	M + T
16	6	8·0	655	T
18	7	9·2	665	T
20	8	10·3	665	T

---

[1] See also Howe and Levy, *Journal of the Iron and Steel Institute*, 1916, No. II. p. 210.

[2] M = martensite ; T = troostite.

The initial temperatures on quenching, that is to say, the temperatures at the commencement of rapid cooling by immersion in water, were on the average 750°; it was found in different experiments that a difference of 40° had, in the case of this steel, no appreciable influence on the form of the curves, or on the abnormalities they presented.[1]

From the point of view of the microstructure the principal constituent is given—that is to say, that which forms almost the whole of the preparation at the centre of the sample. There are sometimes seen in the martensite small patches of troostite, and in the troostite erratic areas of martensite. The authors will revert to these details later; what is here under consideration is the general appearance, apart from little incidental, fortuitous, and accidental local anomalies.

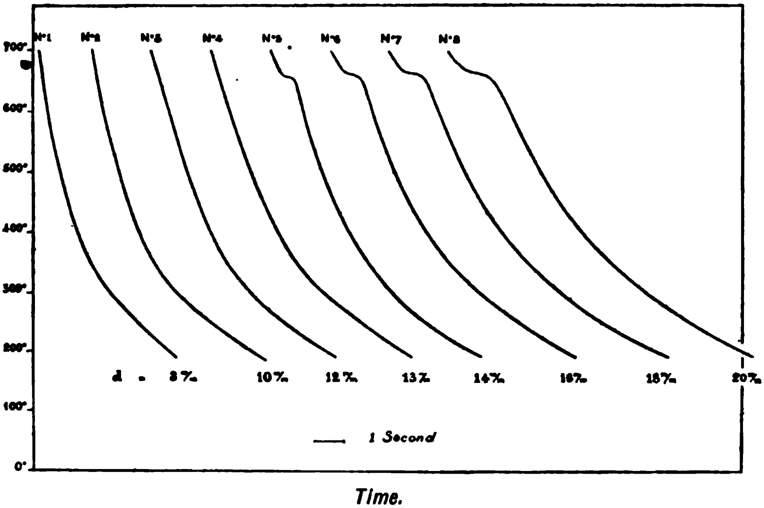

FIG. 31.—Average Cooling Curves at the Centres of geometrically similar Cylinders of Steel containing 1·07 per cent. carbon and 0·08 per cent. manganese, quenched in water.

Fig. 32 gives a facsimile of four curves recorded on the same paper relating to cylinders with increasing diameters which, counting from left to right, were 8, 12, 16, and 20 mms. The samples of 8 mms. were quenched at a lower initial temperature than the others, which shows that this factor does not, in these circumstances, influence the appearance of the phenomena, a point to which further reference will be made later.

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[1] In the case of the cylinder with diameter = 13 mms. (curve No. 4; $\tau = 6''6$), only one experiment was made at a quenching temperature of 750°.

The general considerations which arise can be summarised as follows: (*a*) We will examine the curves in Fig. 31, in the order of increasing rates of cooling—that is to say, in the order of the decreasing diameters of the samples. In curves 8, 7, 6, and 5 (diameters 20 mms. to 14 mms. T, from 10·3 to 6·9 seconds) there will be seen, at temperatures in the neighbourhood of 650°, a transformation point very clearly shown in the usual manner by a well-marked bend. This is the recalescence point, which tends to lower in proportion as the rapidity of the cooling increases within the limits given, but which, nevertheless, remains at a high temperature. Then, suddenly, in curves 4, 3, and 2 this anomaly completely disappears, the curve is absolutely regular down to

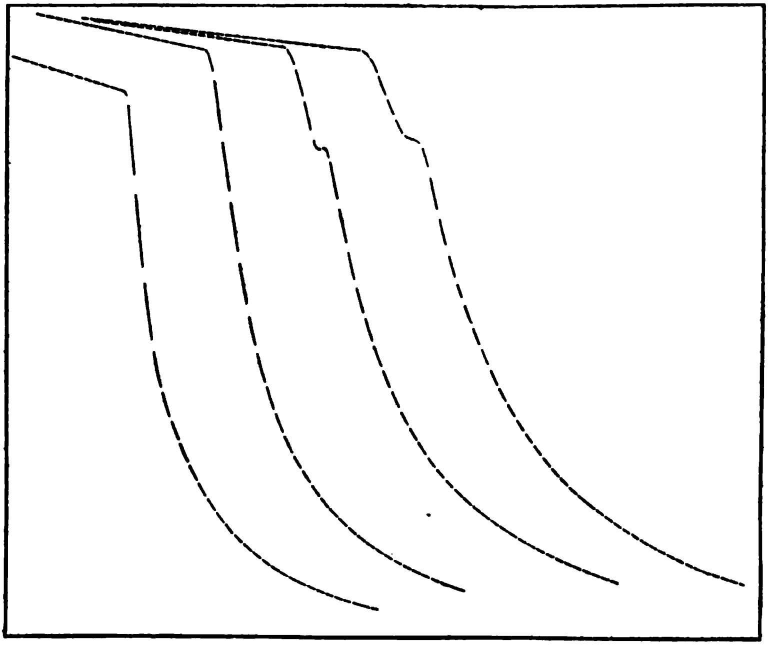

FIG. 32.—Facsimile of Curves recorded from the commencement of the Quenching of the same Steel (Fig. 31) in Cylinders of 8, 12, 16, and 20 mm. in diameter.

about 350°, without any liberation of heat discernible even by the method of comparison with the cooling curves of metals not undergoing any transformation—a comparison made according to the details given in the first part of this paper. On the other hand, it will be seen that the form of the lower portions of the curves below 300° to 350° is altered. This is particularly noticeable on comparing curves Nos. 4 and 5, which are side by side in the figure. There is a gradual diminution in the gradient of the curve, showing a gradual liberation of heat at low temperatures, and this is shown directly by the method of comparison, which reveals the anomaly in a clearly marked manner. Fig. 40 supplies an example for a steel in a succeeding series of experiments.[1]

Thus, the transformation taking place, to begin with, at a high temperature, is suddenly relegated to lower temperatures when we pass from the sample with a diameter of 14 mms. to one with 13 mms., while still maintaining constant the external conditions of quenching; this corresponds with a very slight time variation of 6·9 seconds to 6·6 seconds.

It may therefore be said that there exists a critical range, in the rate of cooling, at which the thermal phenomena characterising the internal transformations change their nature and their position in the temperature scale suddenly, which, for the sake of brevity, the authors have termed the *critical rate of quenching under a definite critical state of quenching and law of cooling.* For simplicity, we will call Ar′ the anomaly distinctly visible on the curves at about 650°, and Ar″ the change in the appearance of the curves at about 300°, without for the moment in any way prejudging the nature of the corresponding transformations.[2]

(*b*) The sudden change that takes place in the internal thermal phenomena can be indirectly revealed by an examination of the periods of cooling. When an evolution of heat takes place at a low temperature its influence on the duration of the cooling is much greater than if an equal or even a greater quantity of heat had been liberated at a high temperature. (See note 1 in the Appendix.) The relegation of the thermal anomaly to a low temperature should therefore reveal itself on the curves $\tau = f(d)$, giving the duration of the cooling, τ, from 700° to 200° in terms of the diameter of the sample. This is shown in Fig. 33, where the representative points, which to begin with lie along a straight line, the continuation of which passes through the point of origin, end, in the case of diameters greater than 14 mms., by falling along another straight line.

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[1] In curves given later much more marked examples of this diminution of the gradient will be given. The progressive divergence which exists at low temperatures, in the experimental cooling curves plotted by Benedicks for a steel with 1 per cent. of carbon, in cylinders 6·5 mms. in diameter, and the theoretical curves as calculated by McCance are not due solely, as the latter states, to a rise in the temperature at the surface resulting from incomplete agitation of the liquid, but also to a progressive internal evolution of heat, accompanied by the formation of martensite, which has completely escaped the attention of these two observers.

[2] This notation, similarly adopted by Chevenard (*Revue de Métallurgie*, 1917, vol. xiv. p. 610), corresponds with that employed by Dejean (*ibid.*, p. 641) under the terms point A and point B. The terms selected appear to the authors preferable to the latter.

Benedicks finds that τ is proportional to the mass of the samples, and that it is very little influenced by the surface, the variations in the masses being, in his experiments, chiefly due to changes in the lengths of the cylinders.

The results obtained by the present authors show, on the contrary, that when employing geometrically similar cylinders τ varies in proportion to the diameter (that is to say, in the ratio $\frac{\text{mass}}{\text{surface}}$, as Le Chatelier had pointed out), but with the express reservation of making a distinction according as the thermal anomaly reveals itself at a high temperature (Ar′) or at a low temperature (Ar″). It should be added that, given the experimental conditions, all Benedicks' curves would display the low temperature thermal anomaly Ar″, which escaped his attention.

(*c*) *Micrographic Examination of the Centre of the Sample.*—An examination of the preceding table, taken in conjunction with the considerations and facts just enunciated, allows of the following conclusions being directly deduced.

The transformation in the vicinity of 650° (Ar′) corresponds with the formation of troostite.

The low temperature transformation (Ar″) corresponds with the formation of martensite.

There is therefore, in the given initial conditions of quenching, a critical rate marking the transition from troostitic quenching to martensitic quenching.

As the rate of cooling decreases from the centre to the periphery, this transition should be noticeable, as the surface is approached, on plane sections of samples, the centres of which are troostitic;

there is, as a matter of fact, an annular outward martensitic zone surrounding the central troostite disc. This is shown diagrammatically in Fig. 34 for the samples as a group. There is naturally a narrow transitional zone between the troostite and the martensite, in which the two constituents are intermingled in proportions which vary rapidly from the centre, outwards. Fig. 34 gives the simplified macrographic appearance of a horizontal median section of the cylinders, thus showing clearly the "depth of hardening." The thickness of the martensitic zone decreases when the radius

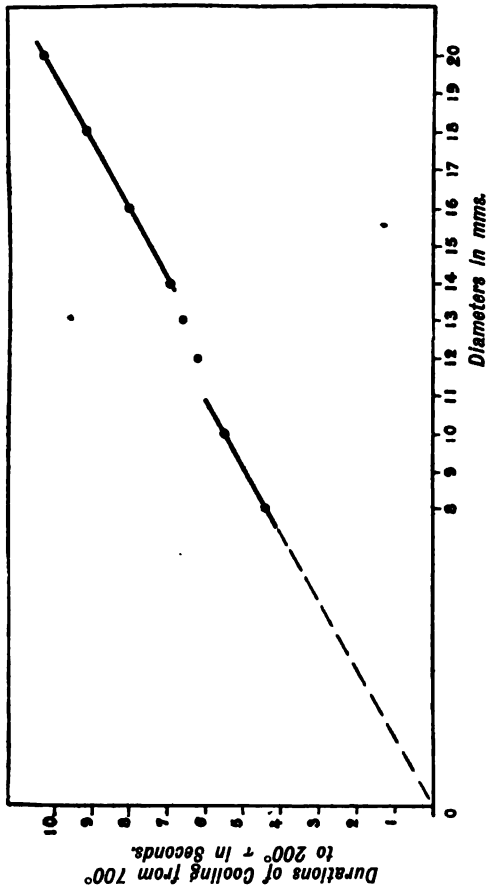
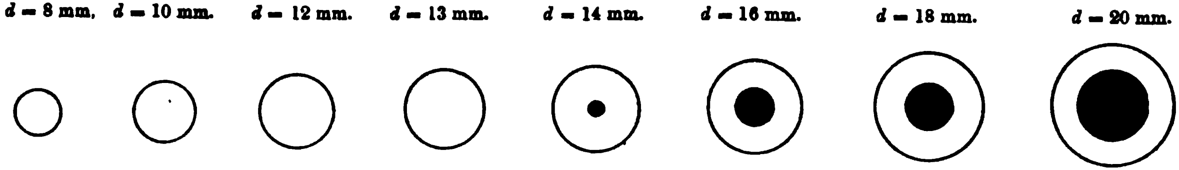
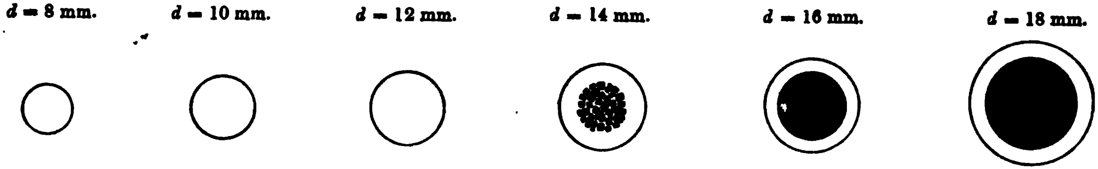


FIG. 33.—Variation in Terms of the Diameters of the Cylinders of the Duration of Cooling from 700° to 200° for the same Steel (Fig. 31), quenched in water.



▭ Martensite Areas. ▬ Troostite Areas.
Hypereutectic Steel (C = 1·07 ; Mn = 0·08).



▭ Martensite Areas. ▬ Troostite Areas.
Hypoeutectic Steel (C = 0·50 ; Mn = 0·13).

FIG. 34.—Diagram of the macrographic appearance after Etching Curves. Sections taken midway through the quenched cylinders with picric acid.

of the curve increases, and there is, in the case of *d* 13 mms., martensite in the centre. (No. 1, Plate XXXII.)

With a diameter of 14 mms. the troostite is already greatly in excess (No. 2, Plate XXXII.), and only very little martensite is present—too little, moreover, to be shown on the curves.

(*d*) *Hardness.*—The following table summarises the results of the determinations of the hardness made on the centres of the samples by means of a ball of 5 mms. under a pressure of 500 kilogrammes.

Diameters of the Cylinders.	700°-200°.	Diameters of the Impression.	Brinell Numbers corresponding therewith.
Mms.	Seconds.	Mms.	Kg./Mm.²
8	4·4	1·03	593
10	5·5	1·06	560
12	6·2	1·01	617
13	6·6	1·01	617
14	6·9	1·16	467
16	8·0	1·26	394
18	9·2	1·22	421
20	10·3	1·26	394

If we plot graphically (Fig. 35) the variations in the diameters of the ball impression, or of the Brinell numbers in terms of the diameters of the cylinders or of τ a discontinuity in the appearance of the curve, corresponding with the critical rate of quenching, is clearly seen. There are, indeed, two regions, one of great hardness, in the neighbourhood of 600 Brinell units; the other of medium hardness, in the neighbourhood of 400 Brinell units.[1] This will, in the sequel, be expressed by the terms "hard martensitic quenchings" and "soft troostitic quenchings." The critical rate of quenching is therefore characterised by a rapid lowering of the hardness, in curves representing this property in terms of the rapidity of cooling.

Any change in the rate occurring in the vicinity of the critical rate may occasion considerable differences in the hardness, whereas similar changes produced under conditions far removed from this rate of speed only cause slight changes in the hardness, or none at all.

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[1] In his experiments on hardening, McCance (*Journal of the Iron and Steel Institute*, vol. xxxix. p. 192) found for hardened martensitic steels (the surfaces of small samples water-quenched) hardnesses reaching and exceeding 700 Brinell units. The differences between the values found by the authors arise, to a considerable extent, from their having effected their own determinations with a 5-millimetre ball under a pressure of 500 kilogrammes, which, contrary to what has been stated by Benedicks (Upsala, Thesis, 1904), does not give hardness values comparable with those obtained by means of a 10-mm. ball and a pressure of 3000 kilogrammes.

This explains the results obtained by McCance[1] on raising the temperature of the water in the quenching bath. The superficial hardness of quenched parts remains constant when the temperature of the water is below 20°; above this and up to 60° very variable results are obtained, and the hardness varies not only from sample to sample, but even in the same sample. This arises from the fact that the neighbourhood of the critical rate is being approached; the least alteration in the surface cooling conditions, the rate of the circulation of the water, the greater or less local liberation of steam, the momentary temperature of the water, &c., suffice to turn a hard quenching into a soft quenching. Now, by hardening in a bath and quenching and agitating the samples in a bucket of water, the mode employed by McCance, these surface conditions are exceedingly variable. The results obtained need therefore occasion no surprise, in view of the conception formed in regard to the critical rate of quenching. From this follows likewise the explanation of the formation of hard and soft zones in the quenched parts described by that author in his paper.

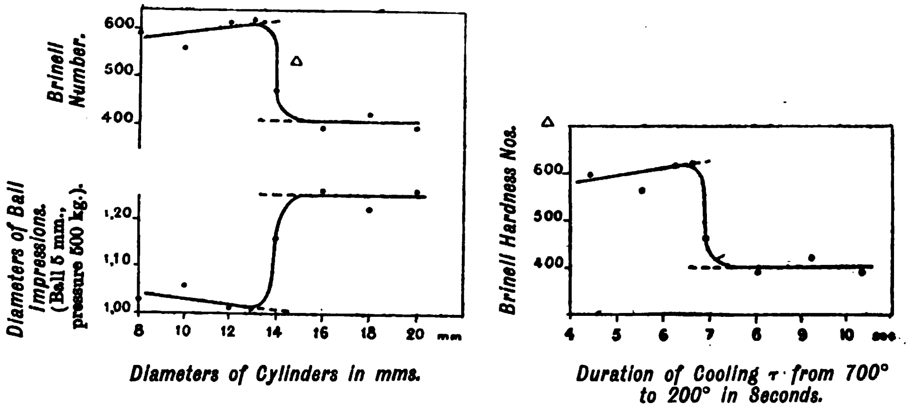

FIG. 35.—Curves showing the variation of the Hardness △ after Quenching, in terms of the Diameters of the Cylinders and of the Duration of Cooling τ from 700° to 200° (steel with 1·07 per cent. carbon and 0·08 per cent. manganese).

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[1] *Journal of the Iron and Steel Institute*, 1914, No. I. p. 192.

If the rate of circulation of the quenching liquid at the surface of the sample be so irregular that at this surface a point here and there is at the critical rate of quenching, there will be superficially obtained martensitic and troostitic zones, and hence, irregular hardness. This can be proved, in particular, in the case of quenching by sprinkling with an insufficient water supply, and revealed subsequently by etching macrographically with picric acid the polished outer surface of the samples: a characteristic marbled appearance is thus obtained (No. 10, Plate XXXIV.).

We thus arrive at a notion of a discontinuity, or at least of a rapid and not gradual variation in the nature of the phenomena accompanying or determining the hardening of carbon steels:

1. By the complete disappearance of the transformation clearly shown in the cooling curves towards 600°–650° (point Ar′).
2. By the appearance of a gradual evolution of heat at a low temperature (below 350°), marked by a diminution in the gradient of the lower portion of cooling curves (anomaly Ar″).
3. By the substitution of martensite for the troostite, corresponding respectively with the Ar″ and Ar′ transformations.
4. By the variations in the relations existing between τ and d in the case of geometrically similar samples.
5. By the examination of the hardness in terms of τ.

It is this border-line, somewhat indefinite in regard to quantitative determination, separating the two modes of occurrence of the phenomenon of transformation—quasi reversible and definitely irreversible—that the authors, for the sake of brevity, call: "the critical rate of quenching for a given initial state of quenching and cooling law."

For rates speedier than this, hard martensitic quenchings occur; for rates slower, soft troostitic quenchings. It should be noted that the troostite is, in this case, always accompanied by cementite, that is to say, by the pro-eutectic constituent (No. 3, Plate XXXII.).

Hypoeutectic Steel d *with* 0·50 *per Cent. of Carbon and* 0·13 *per Cent. of Manganese quenched at about* 750°.

The following table and Fig. 36 gives the characteristic numerical results and the average curves relating to this series of experiments:

Diameter of the Samples.	Number of the Curve in Fig. 36.	τ 700°–200°.	Temperature of the Anomaly distinctly seen on the Curves.	Micrographic Appearance. Chief Constituent.
Mms.		Seconds.	Degrees.	
8	1	3	...	M
10	2	3·8	...	M
12	3	4·5	610	M + (T + F)
	3 bis	4·1	660	not examined
14	4	4·8	660	T + F
16	5	5·4	655	T + F
18	6	6·3	655	T + F

In the case of each sample the different cooling curves were practically superposable, except in the case of the 12 mms. diameter sample. For the latter sample two curves were obtained (Nos. 3 and 3*a*) of Fig. 36, which for one and the same sample are very different. The conditions of cooling had been identical and the quenching temperature the same, inasmuch as they were 845° and 848° respectively—that is to say, differing only by an amount which is within the limits of experimental error.

Curve No. 3 in unbroken line, which was the first obtained, is of the same type as curves 4, 5, and 6 relating to larger diameters, with an anomaly at high temperature Ar′.

Curve No. 3*a* (in dotted line), the second obtained on recommencing the experiment on the sample that had given curve 3, presents both an anomaly at high temperature (Ar′) and a gradual diminution in the gradient at low temperatures (Ar″), as do curves 1 and 2 a diminution seen on comparing them, and shows, besides, by an examination, values for T, which are greater in curve 3*a* than in curve 4, although the sample and the conditions of quenching were the same.

There is therefore, in this instance, a liberation of internal heat at two periods and in two regions of the temperature scale, that is to say, a reduplication of transformation such as has been known to occur in special steels, and in particular, in nickel-chromium and chromium-tungsten steels.[1]

The micrographic examination of the sample which, after quenching, gave the curve 3*a*, shows the simultaneous occurrence of both troostite and martensite, in similar proportions. Thus, in the neighbourhood of the critical rate there may be seen, in regard to carbon steels, a reduplication of the transformation point, and a second heating may further modify the behaviour of the cooling transformations. Apart from this peculiarity the experiments made with this steel lead to the same facts as before. There are two types of cooling curve, Nos. 1, 2, and 3 with anomaly Ar″, and Nos. 4, 5, and 6 with anomaly Ar′; there is still a discontinuity in the behaviour, but this time within narrower limits, as it occurs in one and the same sample.

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[1] See Osmond, Grenet, Portevin and Dejean.

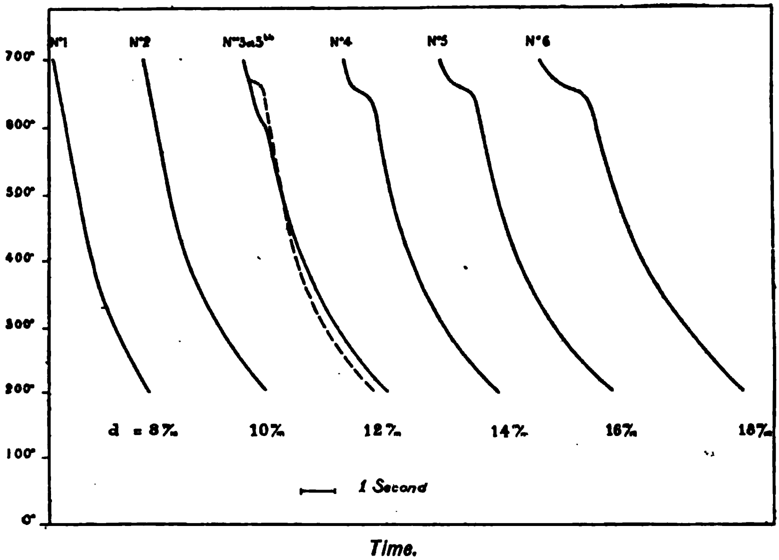

FIG. 36.—Average Cooling Curves at the centres of geometrically similar Steel Cylinders, 0·50 per cent. carbon and 0·13 per cent. manganese, quenched in water.

The last of the curves still shows Ar′, and corresponds with τ 4·5 seconds, whereas with steel *g*, with 1·07 per cent. of carbon and 0·08 per cent. of manganese, there was in this case $\tau = 6·9$ seconds. The critical rate of quenching is therefore higher. Again, if it be sought to ascertain the relationship between τ and *d* practically two straight lines are obtained (Fig. 37), one corresponding with a martensitic quenching and the other with a troostitic quenching. τ may be said to equal *kd*, provided that *k* be given two values, according as $d < 12$ mms. or $d > 12$ mms., both values being applicable when $d = 12$ mms.

Micrographic examination supplies a further proof of the correspondence between martensite and Ar″, and troostite and Ar′.

The results of the macrographic examination of the section at right angles to the axis and midway in the length of the cylinders, represented diagrammatically in Fig. 34, shows, as in the preceding instance, the depth of the hardening, which can also be found by observing the fractured surfaces, owing to the difference in the appearance of the fracture in the martensitic zones and in the troostitic zones (No. 9, Plate XXXIV.).

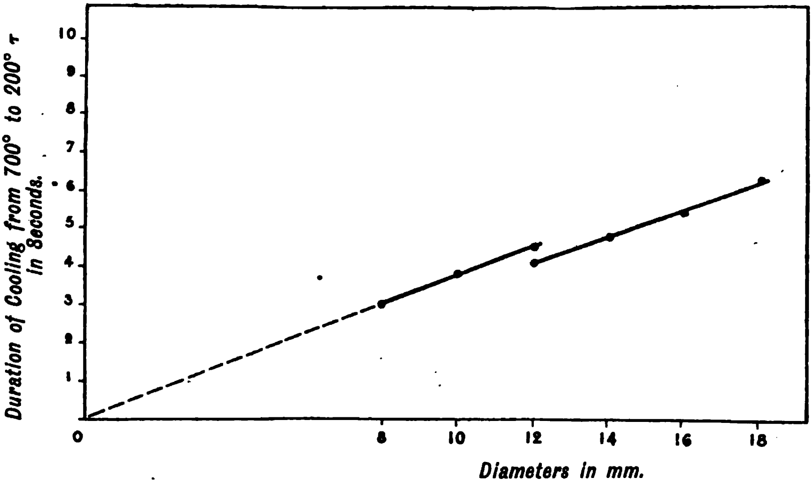

Fig. 37.—Variation in Terms of the Diameters of the Cylinders of the Duration of Cooling τ from 700° to 200° for the same Steel, quenched in water.

Finally, the troostite is always accompanied by ferrite, that is to say, by the pro-eutectic constituent (Nos. 5, 6, and 7, Plate XXVIII.).

Hardness.—The hardness tests made in the centre of the samples by means of a 5-mm. ball under a pressure of 500 kilogrammes, furnish the results given on next page. The transition corresponding with the critical rate of quenching is clearly marked (Fig. 38). There is a variation of over 200 Brinell units when the diameters of the cylinders vary by 4 mms., which corresponds with a modification of 1 second for τ. Beyond the range of this interval the hardness remains nearly constant (see Fig. 38). There is therefore a well-marked separation between the hard martensitic quenchings and the soft troostitic quenchings.

Diameter of the Cylinders.	τ 700°–200°.	Diameter of Impression.	Corresponding Brinell Number.
Mms.	Seconds.	Mms.	Kg./Mm.^{2}
8	3·0	1·05	571
10	3·8	1·05	571
12	4·5	1·17	459
14	4·8	1·32	359
16	5·4	1·31	365
18	6·3	1·30	370

The 12 mms. diameter sample, the centre of which contains similar amounts of troostite and martensite, is of intermediate hardness.

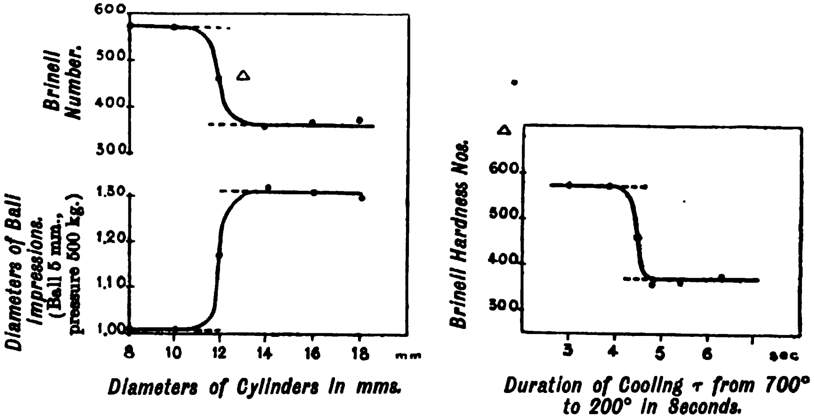

FIG. 38.—Curves giving Variation of the Hardness Δ after Quenching, in terms of the Diameters of the Cylinders and of the Duration of Cooling τ from 900° to 700° for the same Steel (Fig. 36).

An examination of the appearance of the hardness curves confirms, therefore, the preceding results.

Steel f, *Carbon* = 0·81 *per Cent.; Manganese* = 0·21 *per Cent. Quenched at about* 750°.

In this case, even up to diameters of 20 mms., there is no longer found the Ar′ transformation at high temperature, only the diminution in the gradient of the curve at low temperature (Ar″) (see Figs. 39 and 40). The durations τ of the transition from 700° to 200° increase in a way which is very closely proportional to the diameters of the geometrically similar cylinders, and can approximately be represented by $\tau = \frac{d}{2}$ in seconds (d in mms.).

The critical rate is thus much slower, and the period τ which corresponds therewith is longer by 10 seconds, thus exceeding by more than double the values found for the two preceding steels. All the samples after quenching are uniformly composed of what is sometimes called coarse martensite, in thick interlaced but clearly distinguishable needles. This the authors regard and will describe as austenite-martensite.

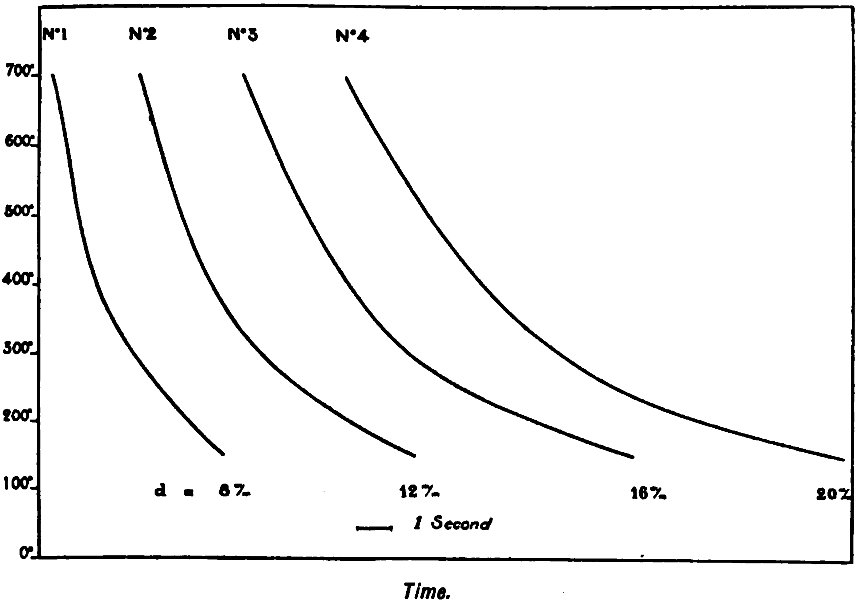

FIG. 39.—Average Cooling Curves at the Centres of geometrically similar Cylinders, containing 0·8 per cent. carbon and 0·2 per cent. manganese, quenched in water.

The hardness at the centre of all these cylinders remains practically constant and high; the ball impressions (ball of 5 mms., pressure 500 kilogrammes) vary from 1·01 to 1·04 mm., which corresponds with the Brinell numbers 617 to 582. The samples have all therefore been hard-quenched. These results are particularly interesting to compare with those obtained in the case of steel *y*, which differs chiefly in the carbon content being nearer to that of the eutectic, and by a slightly higher percentage of manganese. These facts tempt one to ascertain the influence of the chemical composition on the critical rate of quenching.

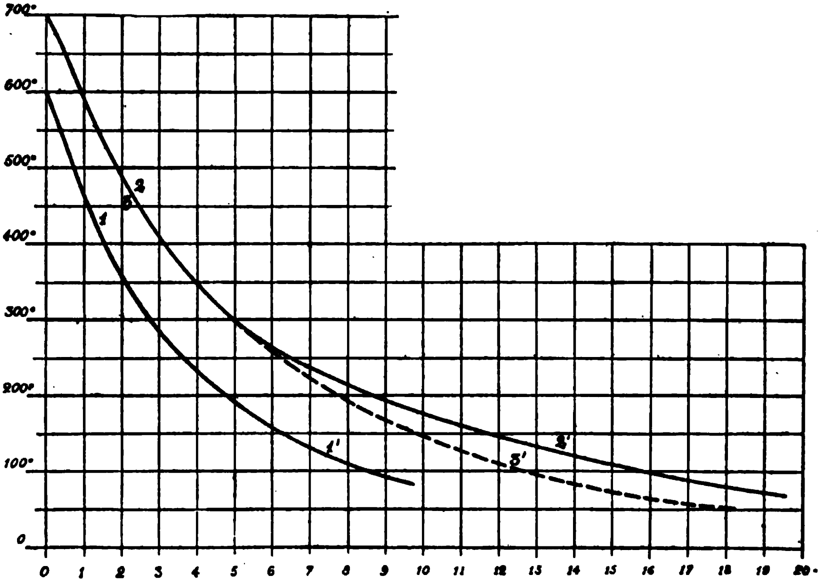

FIG. 40.—Cooling Curves showing Evolution of Heat at Low Temperatures:
1–1 Steel containing 0·8 per cent. carbon and 0·2 per cent. carbon, quenched in water from 630°.
2–2 Steel containing 0·8 per cent. carbon and 0·2 per cent. carbon, quenched in water from 760°.
3–3 Ferro-nickel with 30 per cent. nickel, quenched at 760° in water.

Fig. 41 gives a facsimile of three curves recorded for the 20 mms. cylinder and representing:

1. Cooling in air, with the recalescence locating the transformation point in the temperature scale. (The interruptions in the curve indicate time intervals of 5 seconds.)

2. Cooling in water, from a temperature of 630°—that is to

say, from below the transformation point. In this case there can, naturally, be no anomaly.

3. Quenching in water from 755°. There is no anomaly at high temperature, but if this curve be compared with the preceding one (the two curves having been traced at the same rate of recording speed and the interruptions of the curve corresponding with time intervals of 4 seconds) it will be seen:

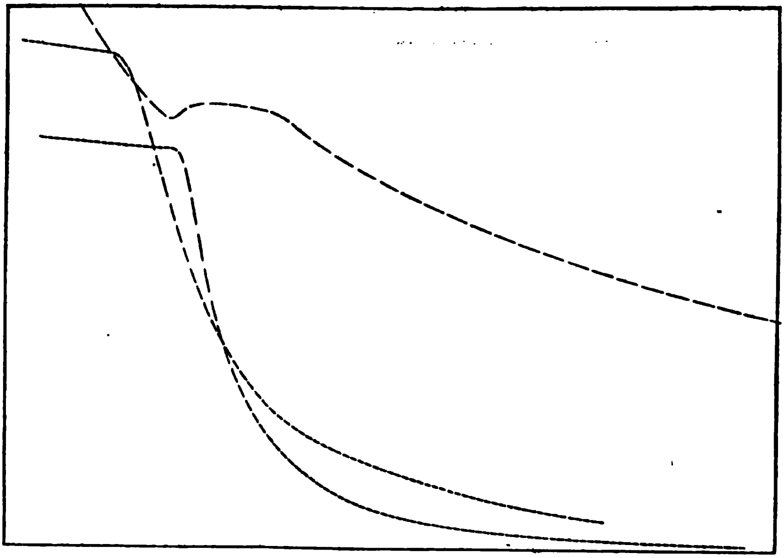

Fig. 41.—Facsimile of Curves registered from the commencement of Cooling for a Steel Cylinder 20 mm. in Diameter, with 0·8 per cent. carbon and 0·2 per cent. carbon. Air cooling with interruptions of the curve every 5 seconds. Water cooling at 630° and 755° with interruptions every $\frac{1}{10}$ second.

(*a*) That the slighter rapidity of cooling on quenching from 755° resulted from the slighter heat conductivity of the steel at the "stable condition on heating" (solid solution of γ iron-carbon).

(*b*) That the gradient of the curve of quenching from 755° is diminished, owing to the formation of martensite at low temperature (anomaly Ar‴).

V. INFLUENCE OF THE CHEMICAL COMPOSITION ON THE CRITICAL RATE OF QUENCHING.

In order to take this into account without unduly multiplying the experiments the authors confined themselves to quenching, under identical conditions of cooling, a series of 16 mms. diameter cylinders prepared from the following steels and quenched in the vicinity of 760°.

	Carbon per Cent.	Manganese per Cent.
c	0·33	0·19
e	0·56	0·29
f	0·81	0·21
h	1·10	0·40
i	1·45	0·20

The results are shown in Fig. 42, and lead to the following conclusions:

1. For the steels *c* and *i* at the opposite ends of the series, with 0·33 and 1·45 per cent. of carbon respectively, the different curves obtained are respectively superposable and have a transformation point Ar′ at high temperature (curves 1 and 5).

2. The same holds good for the two steels nearest to the eutectic, *f* and *h*, with 0·81 and 1·10 per cent. of carbon. The different curves are respectively superposable but do not present an Ar′ transformation point at high temperature, but show a diminution in the gradient at low temperature Ar″ (curves 3 and 4). This diminution is more particularly marked when the neighbouring curves 4 and 5 are compared with them.

These steels have therefore different critical rates, because they are below the critical rate for the two extremes (steels *c* and *i*), and above for the intermediate steels *f* and *h*.

3. There is therefore a minimum in the critical rate of quenching in the neighbourhood of the eutectic. This is clearly shown on comparing the steels *c*, *f*, and *i*, for which the percentages of manganese are identical or differ only within the limits of analytical errors.

4. On the other hand, manganese plays an important part from the point of view of the critical rate of cooling, as we have

here a sample of a 16 mms. steel, *h*, with 1·10 per cent. of carbon and 0·40 per cent. of manganese which is martensitically quenched, whereas we have already seen that with similar conditions of quenching a 16 mms. sample of steel, *g*, with 1·07 per cent. of carbon and 0·08 per cent. of manganese, underwent troostitic quenching, and that this was also the case with a 14 mms. sample.

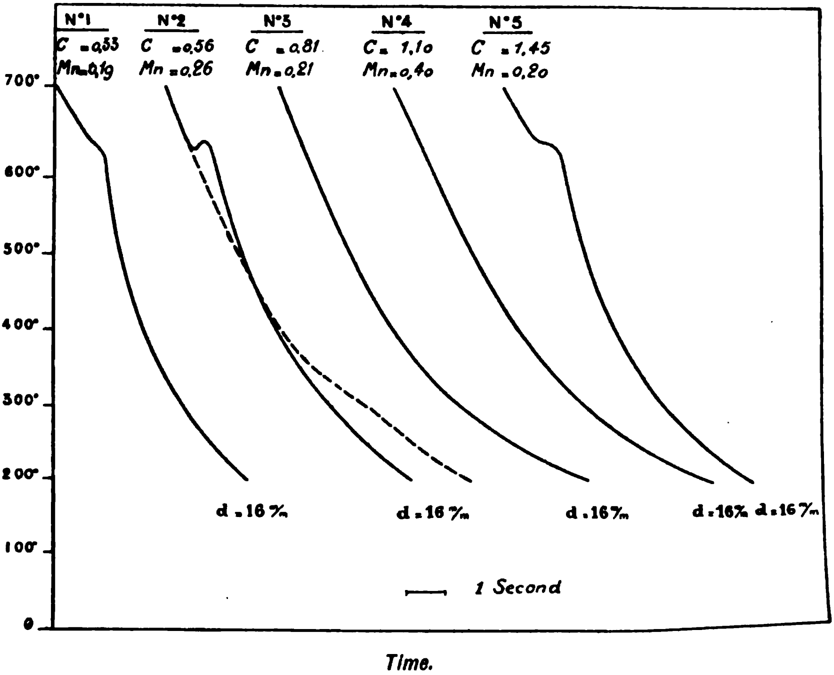

FIG. 42.—Average Cooling Curves at the centres of Cylinders 16 mm. in Diameter of Steel with varying percentages of carbon and manganese.

Here the manganese percentages differ considerably, whereas the carbon percentages are, within the limits of analytical error, the same.

5. If now the steel *e* (carbon 0·56 per cent. and manganese 0·26 per cent.) be considered, two different curves are obtained, shown in the figure at No. 2—one, in unbroken line, has no transformation point Ar′ indicated by recalescence between 635° and 650°; and the other, in dotted line, having no Ar′ transformation,

but a well-marked diminution in the gradient Ar″ at low temperature. The initial quenching temperatures in the two instances were 750° and 758° respectively.

It may be concluded that, as regards this 16 mms. diameter steel, the centre corresponds with the critical rate of quenching, but that, in this case, the initial quenching temperature perhaps plays some part which it may be advisable to investigate, as will be done in the next chapter.

6. The examination of the durations of quenching, τ, from 700° to 200° of these cylindrical samples of the same diameters, of the microstructure and of the hardness at the centre, allows of the same conclusions being drawn. We find, indeed :

Steel.	Carbon per Cent.	Manganese per Cent.	Curves showing the Anomaly Ar′.	Curves showing the Anomaly Ar″.	Microstructure.[1]	Hardness.[2]	
						Mm.	Kg./Mm².
c	0·33	0·19	5·0	...	T + F	1·61	259
e	0·56	0·29	6·5	8·0	M (2nd curve)	1·03	593
f	0·61	0·21	...	8·2	M (+ A)	1·05	571
h	1·10	0·40	...	8·6	M (+ A) + C	1·07	550
i	1·45	0·20	6·5	...	T + C	1·21	428

The duration of the quenching, τ, certainly increases, as stated by Le Chatelier and by Benedicks, with the percentage of carbon, with the important reservation that only cooling curves of the same category be compared, that is to say, showing the same type of anomaly Ar′ or Ar″ on cooling.

The influence of the position of the transformation in the temperature scale, and therefore of the mode in which this transformation takes place, has a much greater reactionary effect on τ than the percentage of carbon.

7. Finally, it is useful to point out that the curves, No. 1 and No. 5, relating to the extreme steels of the series have, below Ar′, a slower average rate of cooling (80° to 85° per second) than the curves relating to other steels in the same range of the temperature scale (100° to 125° per second). This indicates the preliminary segregation of the pro-eutectoid element.

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[1] T = troostite ; M = martensite ; F = ferrite ; C = cementite ; A = austenite.

[2] 5 mm. ball ; pressure, 500 kilogrammes.

Having thus obtained certain broad facts as to the influence of the chemical composition of the steel in relation to the critical rate of quenching, we are led to consider what importance can be attached to the initial temperature of quenching, a question which it was necessary to put in regard to the whole series of experiments, and which is, more particularly, raised by the curves No. 2 relating to steel *e*.

VI. INFLUENCE OF THE INITIAL TEMPERATURE OF RAPID COOLING ON THE CRITICAL RATE OF QUENCHING.

The initial temperature of quenching can have a reactional influence on the phenomena which occur during quenching, owing to two reasons:

1. Its influence on the rate of cooling.
2. Its influence on the internal initial state, and, in particular, in allowing of the more complete disappearance of the pro-eutectoid constituent. This influence may even persist when Ac3 has been exceeded owing to the effect of the persistence of the crystalline particles after the transformation of the surrounding mass, a phenomenon which has been brought into evidence in the experiments of Wyrouboff on the dimorphism of calcium bichromate.[1]

For these two reasons, and owing to the facts brought out in the series of experiments just summarised, a distinction must be drawn according as the rate of cooling differs considerably from, or is closely similar to, the critical rate of quenching of the steel under consideration.

A. *Rates differing considerably from the Critical Rate of Quenching.*

Three examples may be taken from amongst the numerous experiments carried out.

1. *Hypoeutectic Steel* c, *with* 0·33 *per Cent. of Carbon and* 0·19 *per Cent. of Manganese.*

In cylinders of 8 to 20 mms. diameter the rates obtained at the centres were below the critical rate in cases when the initial quenching temperatures were in the vicinity of 750°, while keeping the other conditions of cooling constant. A rise in the initial temperature of quenching does not affect the nature of the phenomena, the curves always showing the Ar′ point. This is shown by the following results:

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[1] The authors have already noted this particular in their "Contribution to the Influence of Annealing on the Structure of Alloys," in the *Revue de Métallurgie*, 1913.

Diameter of the Cylinders.	Initial Temperature of Quenching.	τ 700°–200°.	Anomaly Ar′.
Mms.	Degrees.	Seconds.	Degrees.
14	780	5·4	675
	880	4·8	675
18	780	5·6	670
	880	5·6	670

Raising the temperature of the commencement of rapid cooling by 100° has slightly reduced τ, but the transformation point shows Ar′ at high temperature and the quenching remains troostitic.

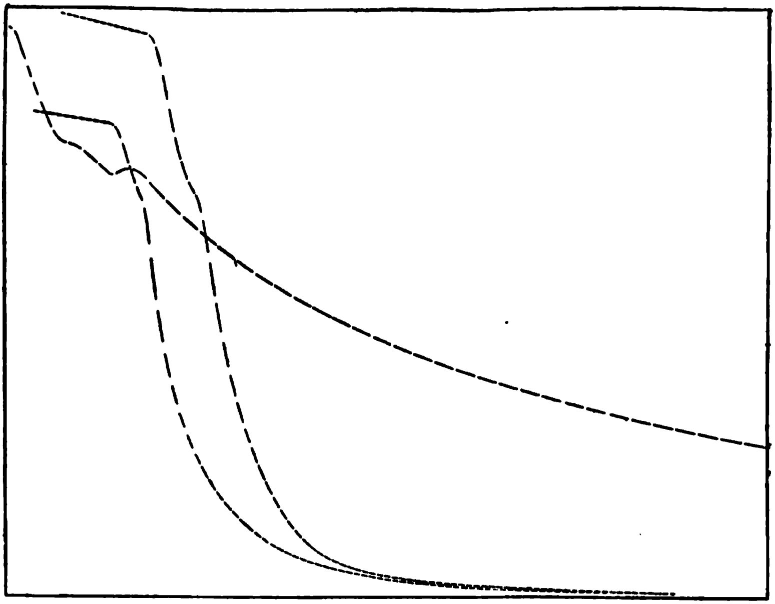

FIG. 43.—Facsimile of Curves recorded from the commencement of Cooling for a Cylinder 16 mm. in Diameter, containing 0·3 per cent. carbon and 0·2 per cent. manganese. Air cooling with interruptions of curve every 5 seconds. Quenched in water at 870° and 750° with interruptions of the curves every $\frac{1}{10}$ second.

Fig. 43 gives a facsimile of the three curves recorded for a cylinder of 16 mms. diameter corresponding with air cooling and quenching at two temperatures. The anomaly Ar′ occurs each time.

2. *Hypereutectic Steel* i *with* 1·45 *per Cent. of Carbon and* 0·20 *per Cent. of Manganese.*

The previous experiments have shown that at the initial quenching temperature of 750° conditions were clearly below the critical quenching temperatures at the centres of cylinders of 8 to 20 mms. diameter. Raising the quenching temperature causes an increase in the average rate of cooling (diminution of τ) without altering the nature of the phenomenon. Ar′ persists and troostite and cementite are invariably found at the centre.

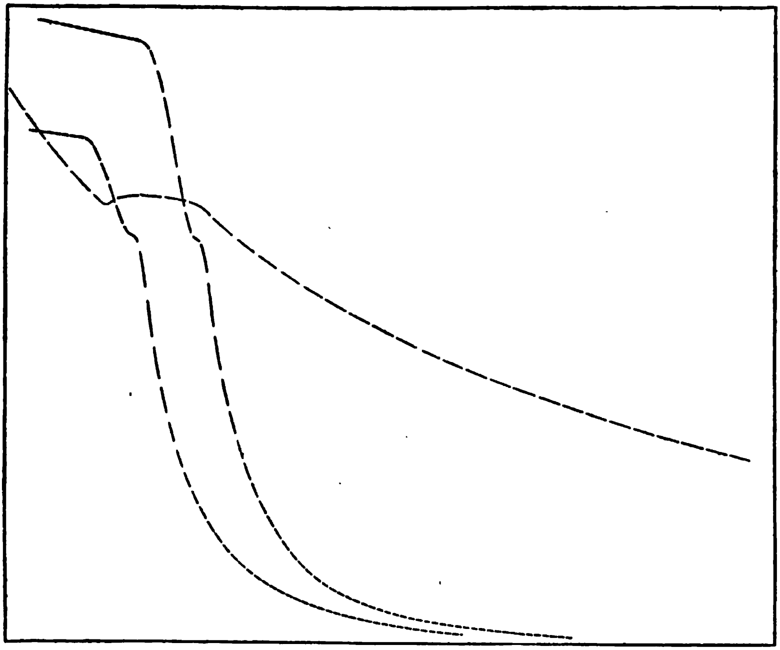

Fig. 44.—Facsimile of Curves recorded from the commencement of Cooling for a Cylinder 16 mm. in Diameter in Steel containing 1·4 per cent. carbon and 0·2 per cent. manganese. Air cooling with interruptions of the curve every 5 seconds. Quenched in water at 900° and 775° with interruptions of the curve every $\frac{1}{10}$ second.

Fig. 44 gives, as before, a facsimile of the three curves recorded for a cylinder of 16 mms. diameter.

Diameter of the Cylinders.	Initial Temperature of Quenching.	τ 700°–200°.	Anomaly Ar.′
Mms.	Degrees.	Seconds.	Degrees.
14	800	5·6	665
	910	4·8	665
18	785	6·8	650
	890	6·0	650

3. *Steel* h *with* 1·1 *per Cent. of Carbon and* 0·4 *per Cent. of Manganese.*

For cylinders of 8 to 18 mms. diameter and an initial quenching temperature of 750°, conditions are beyond the critical rate of quenching for a sample of 16 mms. diameter. Thus, in the case of smaller diameters and in that of the 16 mms. diameter, raising the quenching temperature does not affect the nature of the curves, which always show the Ar″ anomaly at low temperature. A hard martensitic quenching naturally results, with a diminution of τ due to the rise of temperature.

Diameter of the Cylinders.	Initial Temperature of Quenching.	τ 700°–200°.
Mms.	Degrees.	Seconds.
14	780	6·4
	880	5·8
16	780	7·8
	880	7·3

If these experiments be repeated on a sample of 18 mms. diameter it is found that with an initial quenching temperature of 890° only the Ar″ anomaly occurs. The reduplication of the transformation point on cooling (Ar′ and Ar″) occurs when the commencement of the rapid cooling takes place from 790°. At the same time τ diminishes from 9·4 to 9·0 seconds.

Conversely to the previous instances increasing the quenching temperature increases the duration of cooling, because the transformation phenomena change their thermometric position and nature. The critical rate of quenching for $\tau = 900°$ has been exceeded and the critical rate for $\tau = 750°$ has not been reached. We are approaching the following case:

B. *Rates of Cooling approaching the Critical Quenching Rate.*

Let us take steel *e* with 0·56 per cent. of carbon and 0·26 per cent. of manganese (the critical rate of quenching for which corresponds with the cooling at the centre of a 16 mms. diameter cylinder quenched in the vicinity of 750°) and quench cylinders of 14, 16, and 18 mms. diameter at various temperatures, the other quenching conditions remaining constant. The results are given in the following table and the curves of Fig. 45:[1]

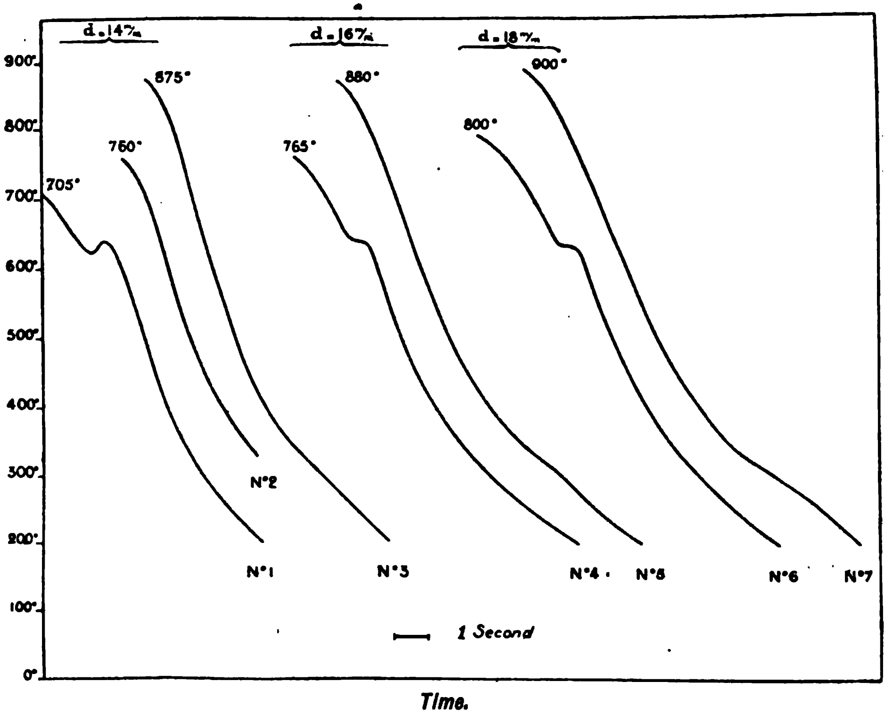

Fig. 45.—Cooling Curves in Steel containing 0·56 per cent. carbon and 0·26 per cent. manganese in Cylinders of 14, 16, and 18 mm. in Diameter, quenched in water from various temperatures.

Diameter of the Cylinders.	Initial Temperature of Quenching.	τ 700°–200°.	Anomalies in the Cooling Curve.
Mms.	Degrees.	Seconds.	
14	705	6·4	Ar′ (620°–635°)
	760*	6·4	,,
	875	5·8	Ar″
16	765	7·2	Ar′ (635°)
	880	7·2	Ar″
18	800	7·0	Ar′ (640°)
	900	7·8	Ar″

---

[1] Curve No. 2 (cylinder 14 mms., quenched from 760°) could not be extended at low temperatures owing to accidents which occurred during the experiments.

It will be seen how clearly the Ar″ diminution of gradient shows itself on the curves Nos. 5 and 7, at low temperatures. In this case the initial quenching temperature has a considerable influence as the action takes place in the vicinity of the critical quenching temperature. The duration of the cooling, τ, increases as the temperature rises, contrary to what is usually believed, because it so greatly modifies the nature of the transformation phenomena. Fig. 46 gives a facsimile of the three curves recorded for a 16 mms. diameter cylinder.

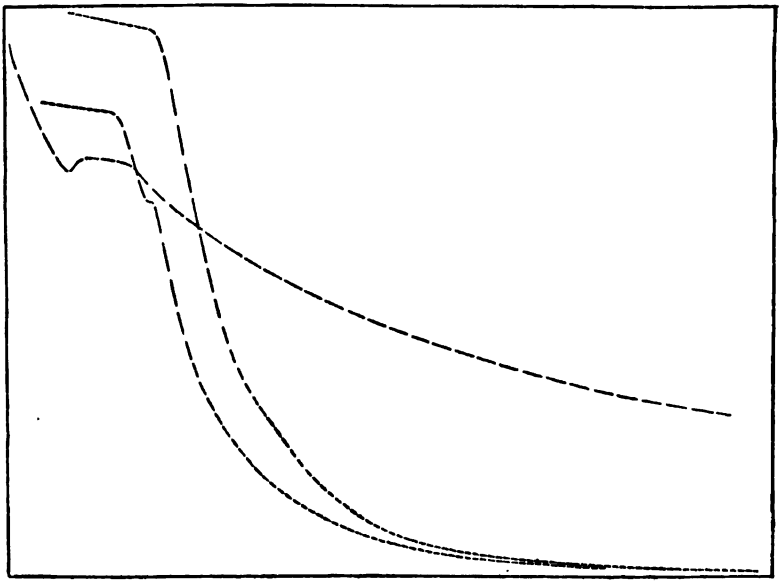

Fig. 46.—Facsimile of Curves recorded from the commencement of Cooling, for a Cylinder 16 mm. in Diameter with 0·56 per cent. carbon and 0·26 per cent. manganese. Air cooling with interruptions of the curve every 5 seconds. Quenched in water at 880° and 765°, with interruptions of the curves every $\frac{4}{10}$ second.

These experiments explain the contradictions met with in the different statements made regarding the influence of the quenching temperature. If very small samples be used, or if the examination be confined to the surface, it is found that the quenching temperature has no appreciable influence on the result (see, for instance, Mr. McCance's results). If, on the contrary, owing to the largeness of the samples or to the external conditions of cooling, the vicinity of the critical rate of cooling be approached, one is led to the opposite conclusion.

When the samples and the conditions of cooling are such that soft troostitic cooling occurs at the centre, there is, naturally, between the centre and the surface, a martensite-troostite region at which the critical rate of cooling operates; the position of this region will shift, therefore, with the initial quenching temperature and the thickness of the zone of hard martensitic quenching will vary. From this arises the importance of quenching from the point of view of the depth of hardening on energetic quenching, particularly as regards large parts.

VII. QUENCHINGS OF LIMITED DURATION.

Lower Limits of the Temperatures of Troostite Formation at Falling Temperatures.

The preceding series of experiments has brought out the fact that the transformations taking place in the course of the rapid cooling of steel present two modes of occurrence:

1. A rapid transformation at a high temperature, Ar′, always above 600° and corresponding with the birth of troostite in the solid solution γ iron-carbon. When, in one way or another, the critical rate is approached, there is a tendency to recalescence (see curves No. 2 of Fig. 42 and No. 1 of Fig. 45), that is to say, to positive acceleration of the rate of reaction when the temperature of the starting of the reaction tends to be as low as possible.

2. A slow transformation at a low temperature, Ar″, nearly always below 350°, and particularly marked below 300°, corresponding with the birth of martensite in the solid solution γ iron-carbon. The acceleration of the rate of reaction diminishes when the temperature of the reaction falls, which occurs when the critical quenching temperature is more and more exceeded. From this arises the partial persistence of the untransformed state, and the appearance of austenite.

In these conditions there can be seen the entire analogy of these phenomena with the well-known phenomena of superfusion and supersaturation. This analogy continues when we consider the influence of the starting of the crystallisation on the reaction, as we shall see later. It may, however, be asked whether it is not possible, by resorting to certain measures, to lower the temperature Ar′ of the direct transformation of the solid γ iron-carbon solution to troostite, that is to say, to an ultramicroscopic complexus of α iron and of Fe_3C. The annealing effect which the birth of this complexus indirectly provokes shows distinctly that this reversion to equilibrium, $\alpha Fe + Fe_3C$, may take place at temperatures well below 600°.

For this purpose the authors had recourse to the arrestation of rapid cooling by limiting the duration of the quenching by withdrawing the sample from immersion in water. For this purpose a pendulum beating seconds was used, and the quenching bath was lowered suddenly at the end of a predetermined period after the immersion, that is to say, from the initial quenching temperature.

In 1904 Professor H. Le Chatelier had already carried out records of cooling curves for limited periods of quenching and had obtained the following results:

With a steel sample containing 0·9 per cent. of carbon and having a width and thickness of 18 mms. quenched in cold water from a temperature of 925°, there were observed on the cooling curves:

A recalescence at 530° to 545° when the period of quenching was limited to 4 seconds.

A bend in the curve at 635° if the duration of the quenching be limited to 2 seconds.

In both cases the metal was completely softened.

In their own experiments the present authors used samples of 10 and 18 mms. diameter, the different periods of immersion depending on the diameter. They selected the three steels:

	Carbon per Cent.	Manganese per Cent.
c	0·33	0·19
e	0·56	0·26
f	0·81	0·20

so as to obtain rapid cooling rates above and below the critical rate of quenching, or in the neighbourhood thereof.

The phenomena observed and the results obtained are given in Tables II., III., and IV., and in Figs. 47–50.

TABLE II.—*Interrupted Quenchings.* I. *Steel* c (*carbon,* 0·33 *per cent.; manganese,* 0·19 *per cent.*).

IA.—*Cylinders of* 10 *Mms. in Diameter quenched at about* 815°.[1]

Approximate Periods of Quenching (Immersion).	Temperatures of Emersion (End of Quenching).	Recalescences observed after Emersion.	Ball Tests.		Micrographic Appearance.
			Diameter of Impression.	Brinell Number.	
Seconds.	Degrees.	Degrees.	Mm.	Kg/Mm.^{2}	
100	10	...	1·17	459	M
2½	330	...	1·18	451	M
1½	460	430	1·55	258	M + (T + F)
½	675	675	1·76	199	T + F
IB.—*Cylinders of* 18 *Mms. in Diameter quenched at* 860°.					
100	10	...	1·62	236	T + F
7	200	...	1·63	233	T + F
3	560	...	1·68	219	T + F
2	670	670	1·94	163	T + F

TABLE III.—*Interrupted Quenchings.* II. *Steel* e (*carbon,* 0·56 *per cent.; manganese,* 0·26 *per cent.*).

IIA.—*Cylinders of* 10 *Mms. in Diameter quenched at* 800°.[2]

Approximate Periods of Quenching (Immersion).	Temperatures of Emersion (End of Quenching).	Recalescences observed after Emersion.	Ball Tests.		Micrographic Appearance.
			Diameter of Impression.	Brinell Number.	
Seconds.	Degrees.	Degrees.	Mm.	Kg./Mm.^{2}	
100	10	...	1·03	593	M
3½	250	...	1·00	630	M[3]
2½	350	...	1·01	617	M
1½	475	455–535	1·43	305	T + F
IIB.—*Cylinders of* 18 *Mms. in Diameter quenched at* 855°.[4]					
100	10	...	1·10	519	M
5	300	...	1·35	343	T + M
4	420	380–395	1·30	370	T
2½	660	650–660	1·58	249	P + F

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[1] See Fig. 47.

[2] See Fig. 48.

[3] Martensite coloured by the tempering effect.

[4] See Fig. 49.

TABLE IV.—*Interrupted Quenchings.* III. *Steel* f (*carbon*, 0·81 *per cent.; manganese*, 0·20 *per cent.*).

IIIa.—*Cylinders of* 10 *Mms. in Diameter quenched at* 825°.[1]

Approximate Periods of Quenching (Immersion).	Temperatures of Emersion (End of Quenching).	Recalescences observed after Emersion.	Ball Tests.		Micrographic Appearance.
			Diameter of Impression.	Brinell Number.	
Seconds.	Degrees.	Degrees.	Mm.	Kg./Mm.^{2}	
100	10	...	1·01	617	M + A
2½	250	...	1·04	582	M + A
1½	500	{485–560 510}	1·37	333	T
1	550	{540–600 565}	1·36	338	T
IIIb.—*Cylinders of* 18 *Mms. in Diameter quenched at* 860°.					
100	10	...	1·02	603	M + A
5	330	...	1·07	550	M + A (diametrical crack at exterior).
4	400	...	1·03	593	M + A (diametrical crack at exterior).
3	580	565–590	1·31	365	T (diametrical crack in centre).

The remarks suggested by the examination of these figures may be summarised as follows:

Cylinders of 10 *Mms. Diameter.*—For the three steels *c*, *e*, and *f*, given the diameter and the quenching temperature, the critical rate of quenching is clearly exceeded so far as the centre is concerned, seeing what has been said before.

In the case of all the interrupted quenchings, martensite, accompanied with considerable hardness, is obtained. If, however, the end quenching be confined to temperatures which are increasingly high, while reducing successively the periods of immersion, it is found that the hardness remains at high values, with the presence of martensite, and no troostite, up to 330° to 350° emersion temperature. On the other hand, when the latter reaches 450° to 500° there is seen, simultaneously:

1. A recalescence after emersion.
2. The formation of troostite and the disappearance of martensite.
3. A considerable fall in the hardness.

---

[1] See Fig. 50.

Cylinders of 18 *Mms. Diameter.*—1. In the case of steel *c*, with 0·33 per cent. of carbon and 0·19 per cent. of manganese and in the experimental conditions adopted, the critical rate of quenching is not reached. There is therefore, in each instance,

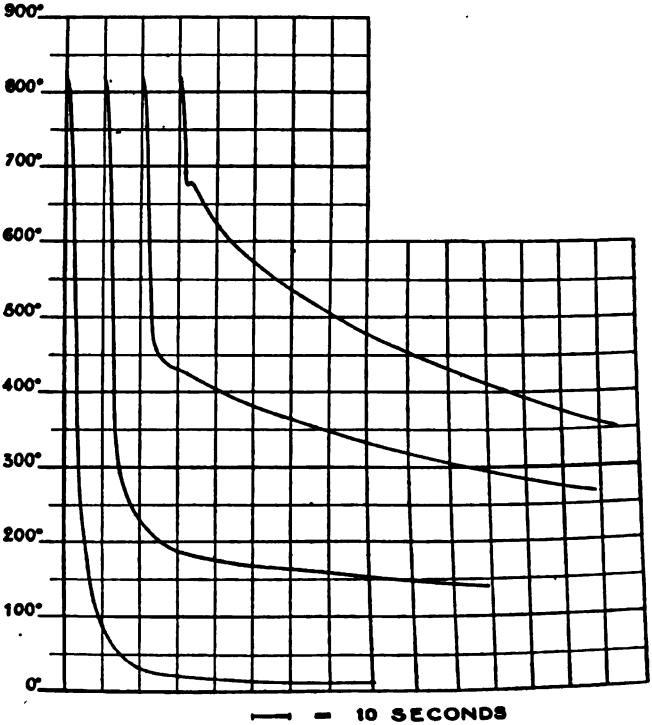


FIG. 47.—Cooling Curves from the commencement of Quenching at about 815° in Water, for a Cylinder 10 mm. in Diameter, with 0·38 per cent. carbon and 0·2 per cent. manganese. Complete quenching and quenchings of limited duration.

soft quenching with recalescence, on falling temperatures, before immersion, the recalescence not being noted on the curves owing to the conditions under which they are obtained. There will thus always be obtained troostite mixed with ferrite, and a medium hardness. Naturally, when the temperature of emersion reaches the temperature of recalescence during quenching (about 650°), recalescence will occur at the emersion ; this is what has occurred in the last sample of Table II. (IB) (approximate period of quenching, 2 seconds; temperature of emersion, 670°). There may then be observed, on micrographic examination, an irregular distribution of ferrite owing to the presence of large areas of pearlite (No. 2, Plate XXXV.).

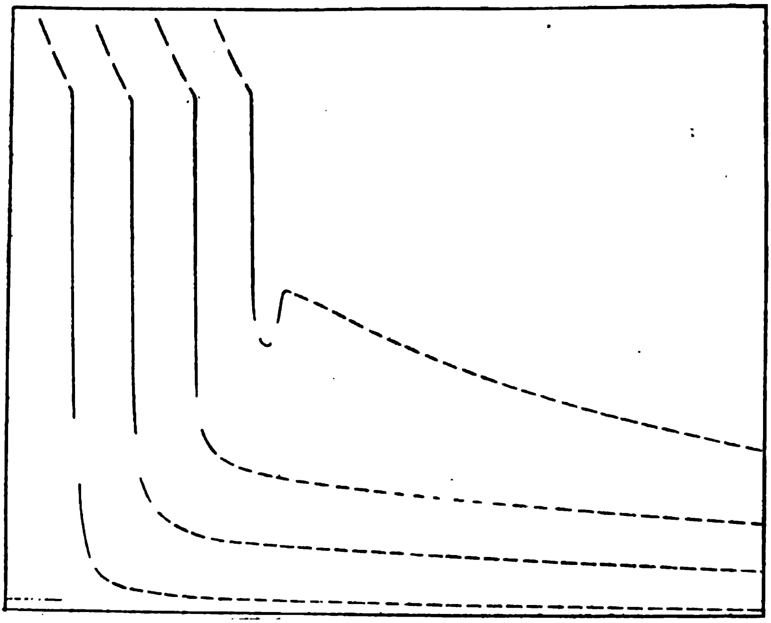


FIG. 48.—Facsimile of Curves recorded from commencement of Quenching at about 800° in Water, for a Cylinder 10 mm. in Diameter, with 0·56 per cent. carbon and 0·26 per cent. manganese. Complete quenchings and quenchings of limited duration, with interruptions of the curves every 5 seconds.

2. In the case of steel *e* with 0·56 per cent. of carbon and 0·26 per cent. of manganese, the conditions are in the neighbourhood of the critical rate of quenching, for, as has already been noted, a rise of 100° in the initial quenching temperature leads to the transition, in the case of 18 mms. diameter cylinders, from a soft troostitic quenching to a hard martensitic quenching. Troostite has already, and as from the emersion at 300°, been produced, but in quantities too small to be shown by a recalescence observable merely by examining the curves.

On the other hand, by emersing at 420°, the temperature of the commencement of recalescence can be lowered down to 380°. The recalescence, which is very clearly marked, has an amplitude of 15° in the ascending scale, and there is complete formation of troostite at low temperature.

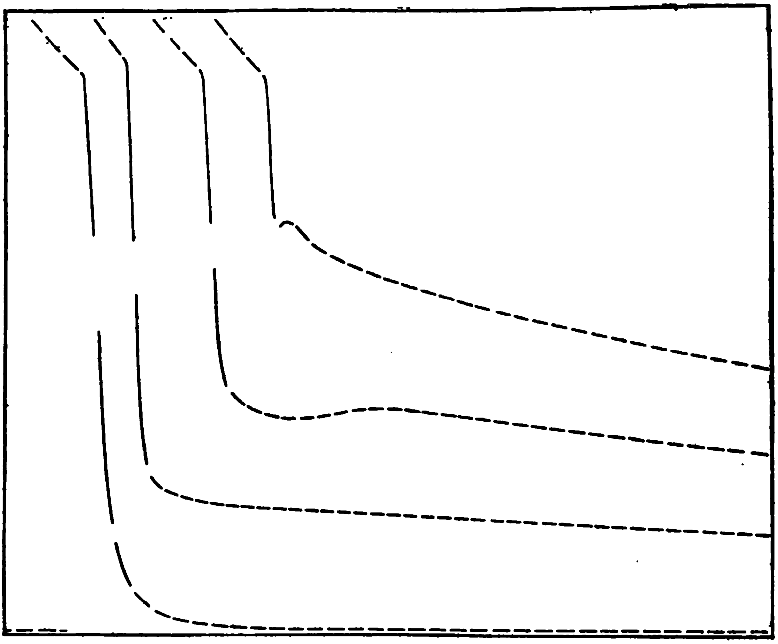


FIG. 49.—Facsimile of Curves recorded from the commencement of Quenching at about 850° in Water, for a Cylinder 18 mm. in Diameter, with 0·56 per cent. carbon and 0·26 per cent. manganese. Complete quenchings and quenchings of limited duration, with interruptions of the curve every 5 seconds.

3. If rapid cooling conditions in respect of which the critical rate of quenching is distinctly exceeded, for 18 mms. cylinders, be employed, as is the case with acid *f*, with 0·81 per cent. of carbon and 0·02 per cent. of manganese, recalescence after emersion does not manifest itself even after emersion at 400°, and, up to that temperature, a martensite-austenite structure persists. After emersion, however, at 580° a recalescence with a 15° margin in the ascending scale is observed and pure troostite

is obtained, with a marked lowering of the hardness. The authors have pointed out, in the last column of Table IV. (IIIB), the curious fact that in this series of experiments only the cylinder quenched to complete cooling in water was free from cracks. They will revert presently to these phenomena.

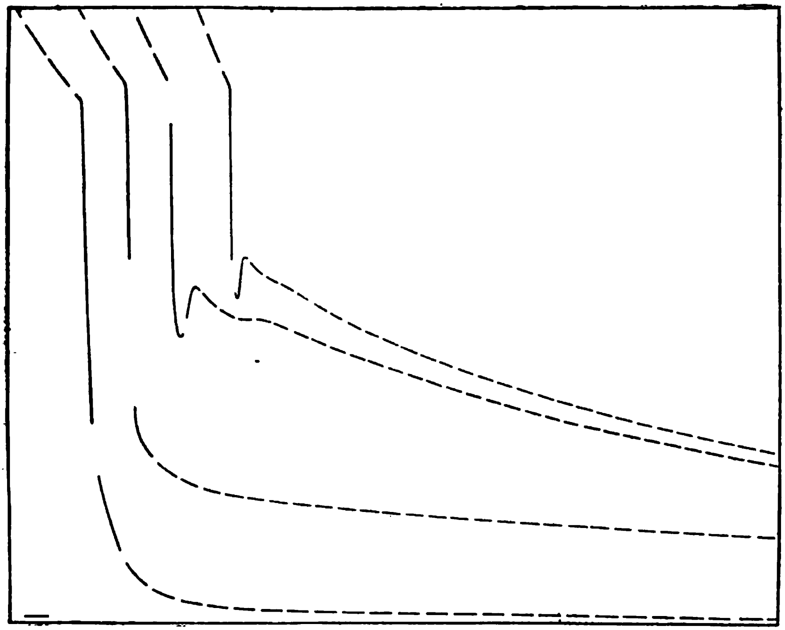
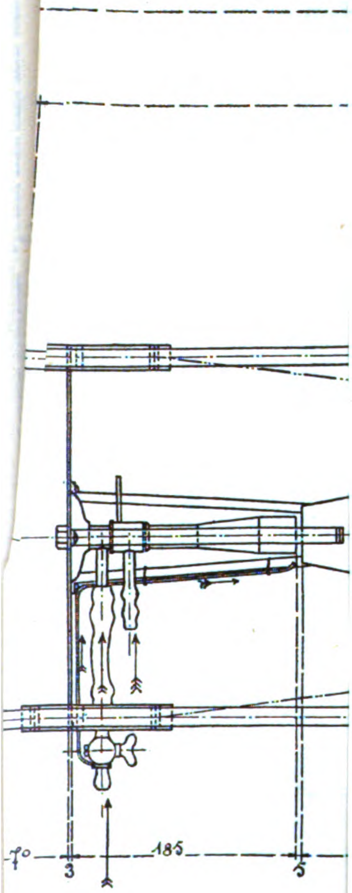


Fig. 50.—Facsimile of Curves recorded from the commencement of Quenching at about 825° in Water, for a Cylinder 10 mm. in Diameter, with 0·8 per cent. carbon and 0·2 per cent. manganese. Complete quenching and quenchings of limited duration, with interruptions of the curve every 5 seconds.

To sum up, the following conclusions are arrived at:

1. With rates of quenching distinctly higher than the critical rates it was possible by the method of limiting the duration of the rapid cooling, that is to say of the quenching proper, to lower the temperature of the recalescence Ar′ down to 450°. As energetic quenching is involved, the solid solution of γ iron-carbon which occurs at high temperatures persists, for the reason previously noted, during the rapid cooling, down to 300° or 350°;



. 8.—View of heating and que

PLATE XXIX.

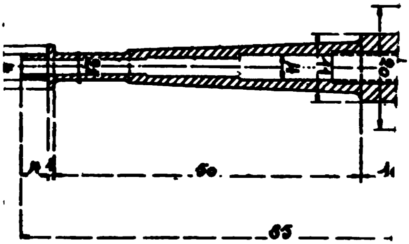
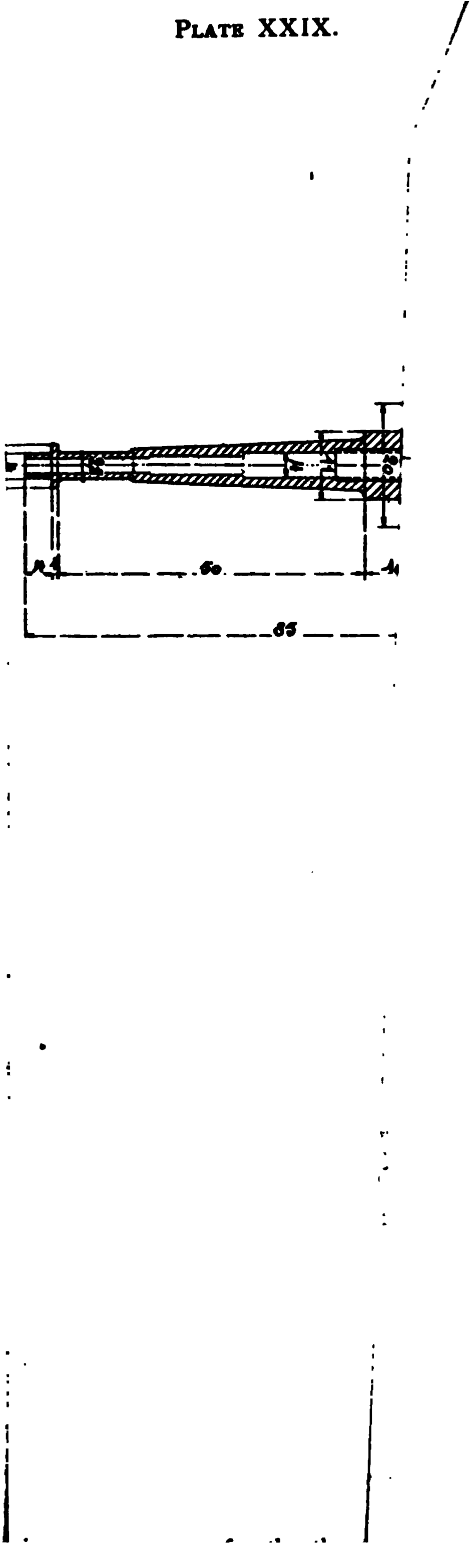
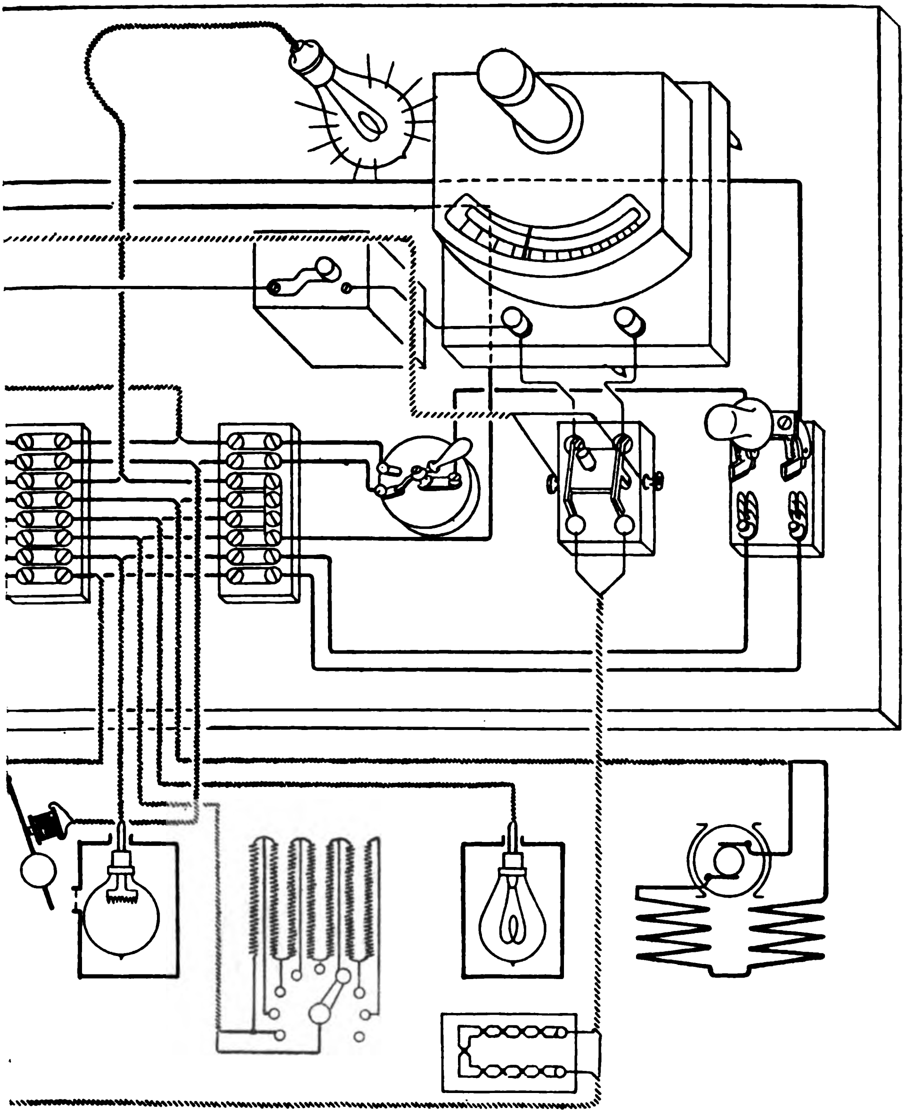


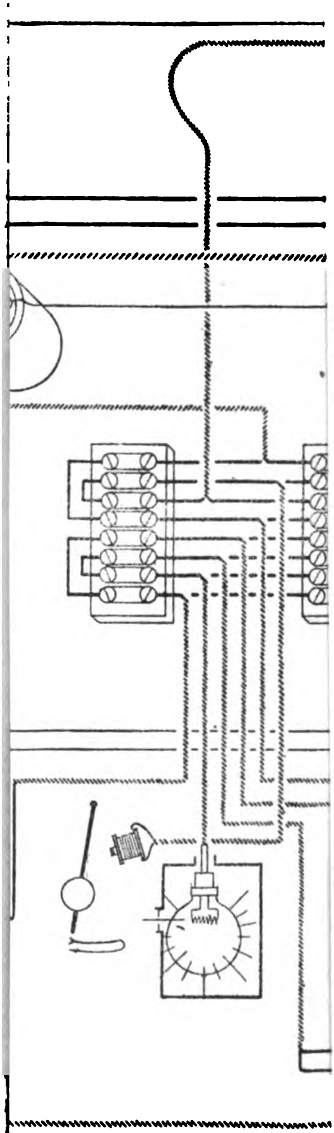
PLATE XXIX.





connections showing the heating arrangements.

.II.



able of connections showing

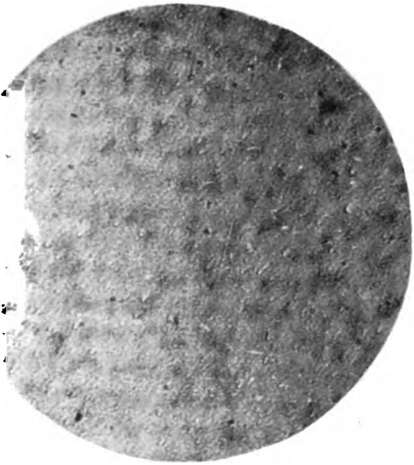
3% Mn.
at 750°.
rtensite.

)% Mn.
at 748°.
rtensite.

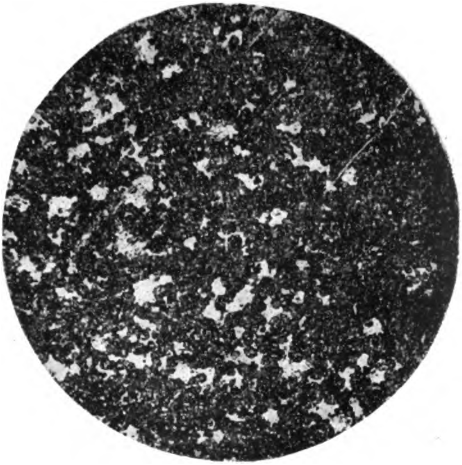
544.

PLATE XXXII.

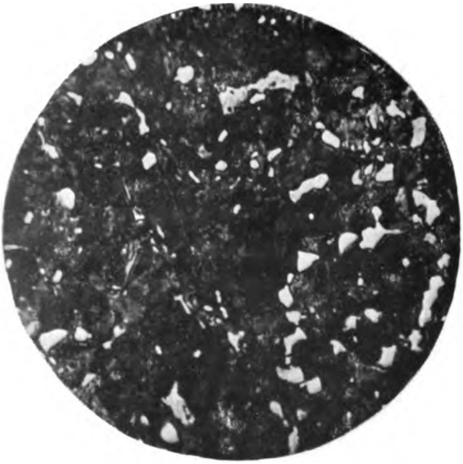
Etched for one minute with a 4 per cent. solution of metanitrobenzolsulphonic acid in ethylic acid.



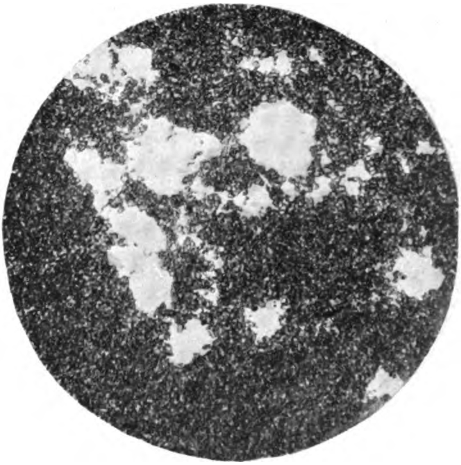
No. 1. Steel g, with 1,07% C. and 0,08% Mn. Cylinder of 13mm. diameter quenched at 750°. T = 6,6 sec.; $\Delta = 617$. Martensite. × 75.



No. 2. Steel g, with 1,07% C. and 0,08% Mn. Cylinder of 14mm. diameter quenched at 750°. T = 6,9 sec.; $\Delta = 467$. Troostite and Martensite. × 75.



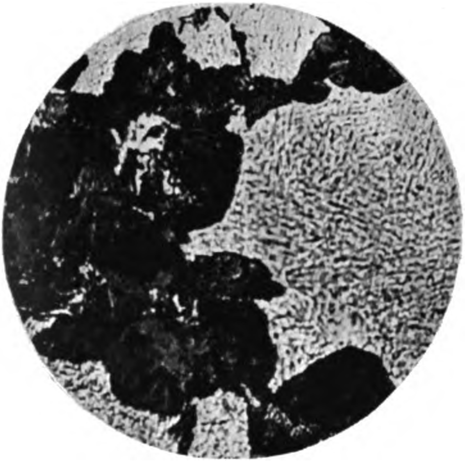
No. 3. Same as No. 2. Highly magnified. Cementite and Martensite. × 870.



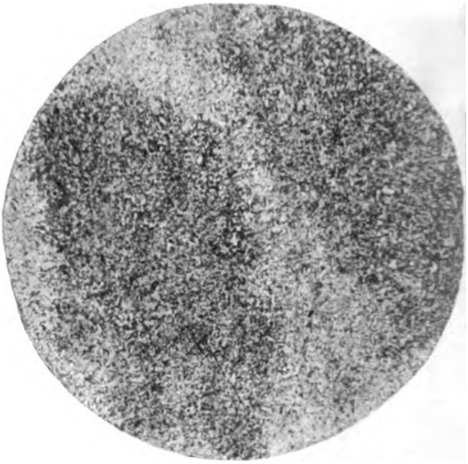
No. 4. Steel d, with 0,50% C. and 0,80% Mn. Cylinder of 12mm. diameter quenched at 748°. T = 4,5 sec.; $\Delta = 459$. Troostite and Martensite. × 75.

[*To face page* 544.

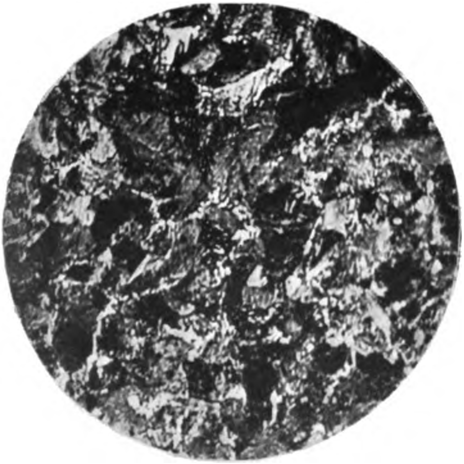
Etched for one minute with a 4% solution of metanitrobenzolsulphonic acid in ethylic acid.



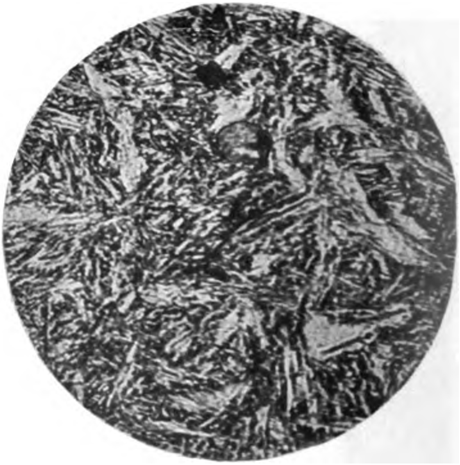
No. 5. Same as No. 4, plate VI. Considerably magnified. Troostite, Ferrite, and Martensite. × 870.



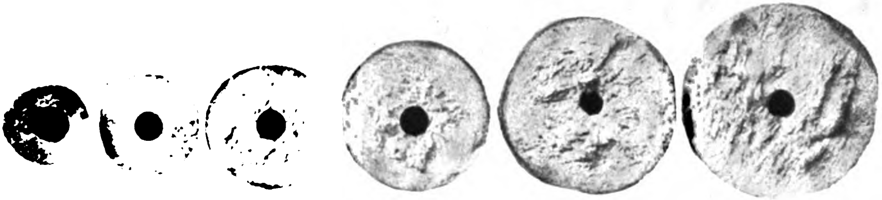
No. 6. Steel d, with 0,50% C. and 0,30% Mn. Cylinder of 14mm. diameter quenched at 750°. $T = 4,8$ sec. ; $\Delta = 859$. Troostite and Ferrite. × 75.



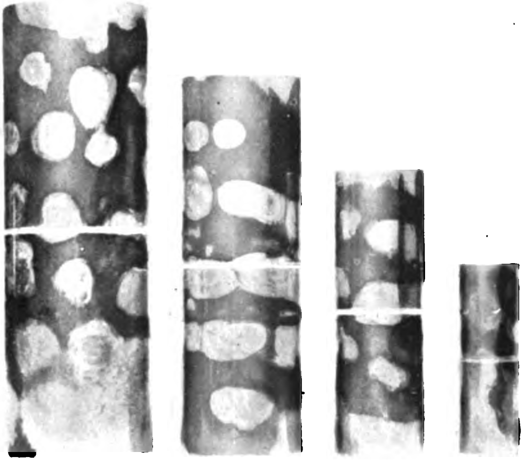
No. 7. Same sample as No. 6. Highly magnified. Troostite and Ferrite. × 870.



No. 8. Steel f, with 0,81% C. and 0,21% Mn. Cylinder 18mm. diameter quenched at 860°. $T = 9$ sec. ; $\Delta = 593$. Austenite and Martensite. × 870.

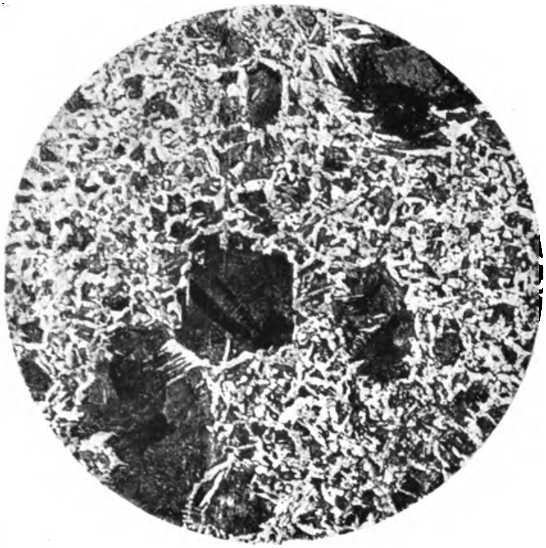


No. 9. Hypoeutectic Steel d, with 0,50% C. and 0,18% Mn. Fracture mid-length in cylinders 8, 10, 12, 14, 16, and 18 mm. diameter, showing the depth of penetration of the hardness by the difference in the appearance of the troostitic and the martensitic areas.



No. 10. Steel g, with 1,07% C. and 0,08% Mn. Quenched at about 750° in the sprinkling appliance. View of the cylindrical surfaces polished and etched with picric acid.

PLATE XXXV.



No. 11. Irregular distribution of the ferrite in a steel containing 0,83% of carbon quenched in water at 860° and interrupted at 670°. Centre of a cylinder 18mm. in diameter. × 200.

No. 12.

below this temperature, and from the commencement of an uninterrupted quenching it undergoes the Ar″ transformation which leads to the birth of martensite. It is therefore a direct and immediate transformation of the solid troostite solution which is caused in such cases at a temperature which is distinctly lower than that at which it has been usually observed to occur hitherto; this reaction has a positive acceleration which manifests itself by a well-marked rise of temperature in the curves recorded.

On the other hand, if the indirect and irreversible method of annealing after energetic quenching be adopted, that is to say by the intervention of the martensite state, the reaction, even in the same temperature ranges, is greatly delayed. The procedure is different.

2. In the neighbourhood of the critical quenching temperature it has been possible to observe the commencement of the direct reaction at temperatures even lower, viz. 380°.

3. In the case of quenching rates lower than the critical rate, recalescence having occurred at a high temperature during the course of rapid cooling, troostite is always found, and the degree of the temperature of emersion does not appreciably alter the structure, or, consequently, the hardness.

4. In the case of energetic quenchings (at rates higher than the critical rate), apart from the slight diminution in the hardness due to the annealing effect, it may be seen that it is possible, without notably affecting the hardness, to stop the quenching at temperatures ranging up to 350°. It should here be clearly understood that what is involved is the actual temperature at a given point within the sample and not a surface temperature, or an " average temperature " ascertained by calorimetric methods. We thus obtain an upper limit for the arrestation of quenching, from the point of view of the hardening which results from this operation, but, owing to the cracks observed in one series of the experiments, it is perhaps safer not to seek to profit by the whole margin of immersion temperature which is thus available.

However this may be, the authors believe that, from the practical point of view, they have, this time, secured information hitherto lacking in regard to the real upper limit of immersion temperatures.

VIII. EFFECT OF THE CRYSTALLINE PARTICLES ON THE CRITICAL QUENCHING RATE AND ITS CONSEQUENCES.

If we review the series of statements made in the course of the experiments hitherto described, we find ourselves in the presence of the following facts:

1. The critical rate of quenching, for a given initial quenching temperature, approaches its minimum in the neighbourhood of the eutectic composition. (Section III.)
2. Raising the quenching temperature in the neighbourhood of the critical rate tends to make Ar′ disappear. (Sections V. and VI. and curves of Fig. 45.)
3. A second quenching tends similarly, if the critical rate be closely approached, to make Ar′ disappear. (Section IV. and curves No. 2 of Fig. 42.)
4. With steels the percentage of carbon in which is far removed from the eutectic proportions, segregation of the proto-eutectic element (ferrite, or free cementite) manifests itself, before Ar′, by a diminution in the cooling curve. (Section IV. and curves 1, 2, 3, and 5 of Fig. 42.)
5. The troostite in the non-eutectic steels is always accompanied by the pro-eutectic constituent; the proto-eutectic elements being, generally speaking, surrounded by the troostite.

This brings out strongly in evidence the *rôle* of the crystalline particles visible under the magnifications at the authors' disposal. The presence of ferrite or of cementite, the constituent elements of troostite, favour the separation of the latter within the solid γ iron-carbon solution. These crystalline starting-points, either visible or ultra-microscopic, may exist either as the result of the non-solution of the pro-eutectic elements at the commencement of the heating, owing to the duration of the heating being insufficiently prolonged, or because the temperature reached has not been high enough, or as the result of the segregation of these elements during the period of the commencement of the heating.

These phenomena would be accentuated to start with if, before heating, the elements be coarser or further apart, which would hamper the complete chemical homogenisation of the solid solution at the commencement of heating, or if various causes conduced, on cooling, to the precipitation of the pro-eutectic element. The presence of inclusions is, in particular, known either by their physical action (Ziegler) or by their chemical action (Giolitti and Zublena) to be a determining cause of the formation of ferrite or of cementite from the commencement of cooling ; it will therefore influence the critical rate of quenching.

These considerations are, however, all only particular instances of the definition of the initial state of quenching, as stated in paragraph 1 of the second part of this paper. In order not to labour unduly the influence and results of this initial state, the authors will confine themselves to the several points which follow. There will thus be seen the effect of the intervention of the following factors, which it will suffice to enumerate, on the critical rate of quenching :

(*a*) The duration of the heating.

(*b*) The size and distribution of the structural elements of the steel before heating.

(*c*) The presence of inclusions.

The critical rate of quenching can therefore vary for the same steel and the same initial quenching temperature, according to the heat treatment it has previously undergone, and in particular, any prior treatment which has the result of increasing the fineness of the elements will increase the critical rate of quenching, and may subsequently play the part of a "previous" treatment.

As the presence and distribution of inclusions may vary according to the process by which the steel has been made (converter, crucible, or open-hearth, or acid or basic process) and the conditions of teeming, the critical rate of cooling may be modified by such cause. Without emphasising these problems, the solution of which is beyond the scope assigned to the present investigation, it will be immediately seen that the influence of the size of the structural elements, of the percentage of manganese, and of inclusions, allow of specially explaining the peculiarities to which the quenching of steel gives rise, according to the process of manufacture and mode of treatment adopted at the steelworks, from the threefold point of view of the depth of penetration of the hardening, the range within which hardening takes place, and the frequency with which cracks occur.

X. Conclusions.

The general conclusions to be drawn from this investigation have already been briefly summarised in the communications presented to the Academy of Sciences on May 14 and June 4, 1917, but the limited space allowed for such communications prevented their being afforded the full development given them in the course of this paper, and certain details had even to be passed over entirely for that reason.

If the views obtained in the successive series of experiments which form the subject of the preceding sections be recapitulated one by one, it is possible to formulate the following conclusions in regard to carbon steels :

1. During the course of a single cooling, that is to say, with a temperature falling regularly, the formation of troostite corresponds with a rapid transformation at a high temperature (about 650°), and that of martensite with a transformation which is relatively slow as compared with the former, and takes place at a low temperature (about 300° and under).

This has been confirmed by the dilatometrical investigation of the cooling of fine wire in nitrogen and in hydrogen by Mr. Chevenard,[1] and agrees with what has for a long time past been known from the investigation of self-hardening chromium-tungsten steels and chromium-nickel steels. Recently Mr. Dejean [2] has verified it for self-hardening nickel and manganese steels.

2. These transformations are shown on the cooling curves by anomalies—one, clearly visible by simple examination of the temperature-time curves (Ar′) ; the other marked by a simple change in the gradient, sometimes visible on inspection of the curves, but in any case discernible on comparing them with the cooling curves of metals and alloys not presenting transformation points, bearing in mind the principles of comparing curves laid down in the first part of this paper.

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[1] *Comptes Rendus*, 1917, vol. clxv. p. 59. Mr. Dejean (*Revue de Métallurgie*, 1917, vol. xv.) also carried out experiments on quenching carbon steels, but the present authors are unable to express any opinion respecting the anomaly he describes as occurring at about 100°, seeing that the conditions of recording the curves are not given, and taking into consideration the size of the samples which, after quenching, were all troostitic (τ, 700° to 100°; varies from 1½ minutes to 12 seconds).

[2] *Comptes Rendus*, 1917, vol. clxv. p. 183.

3. If, in the case of the same steel and the same initial temperature of cooling, the rate of cooling be accelerated or, more correctly, the average rate of cooling, in accordance with the laws as to similar coolings, the lowering of the transformation point does not take place uniformly. There is a discontinuity, or at least a variation, in the position of the transformation, which is not a gradual one. After having been gradually lowered the cooling anomaly shifts from the position Ar′ to the position Ar″, whence is derived the conception of a "critical quenching rate." In reality this expression, which the authors have adopted to describe the phenomena they wished to draw attention to, although a simpler phrase, ought to be replaced by the description "critical zone of rate of quenching" (or hardening) if the phenomenon of the doubling of the transformation point resulting in the presence of troostite and martensite be taken into consideration. As one of the present authors has pointed out in connection with nickel-chromium steels,[1] there is a minimum rate of hard martensitic quenching, with a single transformation, Ar″, at low temperature and a maximum rate of soft troostitic hardening, Ar′, at high temperature. Owing to the experimental difficulties arising from the rapidity of these phenomena, they have not been able actually to define these two rates, which are, at all events, very close to one another in carbon steels, hence the adoption of a single term to express these two designations. Analogous conditions apply in respect to quenching temperatures.

For the special steels, experimental investigation will be found incomparably easier, as these phenomena can be observed for much slower rates of cooling, and the arrangements, which have for a long time past been employed for the experimental study of critical points, would readily bring them out. What, however, the present authors consider it essential to point out is that, as regards rates which are closely similar, the appearance, general laws, and results of the phenomena are identical.

4. This critical rate of quenching is marked not only, as has been said, by the position of the anomalies on the cooling curves, but is also shown :

(*a*) By the examination of the microstructure, in relation to the rapidity of cooling.

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[1] Portevin, *Revue de Métallurgie*, 1917, vol. xiv. p. 107.

(*b*) By studying the duration of quenching τ, in relation to the diameters of geometrically similar cylinders.

(*c*) By studying the hardness in relation to the duration of cooling,

starting, in each case, with the same initial state at the commencement of cooling.

5. There are therefore hard martensitic quenchings (energetic quenchings) or soft troostitic quenchings, according to the position of the cooling transformation, and it has been possible, in the case of carbon steels, to observe the phenomenon of the doubling of the point of transformation which, in the case of special steels, has for a long time past been known to occur. In such case, the simultaneous occurrence of both Ar′ and Ar″ in the course of a single cooling leads to the co-existence of troostite and martensite.

6. In identical conditions of heating and of the law of cooling the critical rate appears to present a minimum near the eutectic composition, and on the other hand, to decrease with the percentage of manganese.

7. Various authors have deduced conclusions relating to the influence of the mass of the samples, and of the agitation of the quenching liquid on the duration of the quenching; and as to the influence of the temperature of quenching, and of the temperature of the water on the surface hardness. These conclusions are valid only so long as the field of investigations does not include the critical rate. For example:

(*a*) With geometrically similar cylinders, the duration of cooling τ increases proportionally with the diameter—that is to say, in the ratio of mass : surface, which is confirmed by the results given by Professor H. Le Chatelier and discussed by Dr. Benedicks, yet a discontinuity is observable when the critical rate is involved.

(*b*) In the case of energetic quenchings (the surfaces of small samples) the hardness after quenching is not appreciably affected by raising the quenching temperature (McCance). On the other hand, in the vicinity of the critical rate the quenching temperature may have a well-marked influence.

(*c*) The agitation or the rate of the circulation of the water in the quenching bath has little effect on the hardness or on the duration of the cooling in the case of energetic quenchings—that is to say, when it operates well above the critical temperature. This is no longer the case when this rate is approached. Similar considerations apply in respect of the temperature of the water.

8. The initial state has considerable importance, because of the action of the crystalline particles, which tend to diminish the lag in the transformation of the solid γ iron-carbon solution, and to provoke, as a result, the formation of troostite. The part these crystal starting-points play is shown by the effect of raising the temperature of quenching, and of repeated quenchings in the neighbourhood of the critical rate, by an examination of the cooling curves above Ar′ in regard to steels of composition far removed from the eutectic, by the fact that the critical rate of quenching is at a minimum in steels approximating to the eutectic composition, and by the presence of the pro-eutectic constituent which always accompanies the troostite in steels differing from the eutectic composition.

This influence of the crystalline starting-points extends to cases where their minuteness leads to their escaping recognition by the actual methods of investigation employed when it arises that the following factors influence the result:

The duration of the heating before quenching.

The size and original distribution of the structural elements.

The presence of inclusions.

The treatment preparatory to quenching.

From the foregoing there may be derived the explanation of many practical facts relating to depth of hardening, range of hardening temperature, and the frequency of cracks.

9. Troostite represents, in the state of extremely subdivided elements not visible under the microscope, the system in the chemically stable state in the cold—that is to say, the mixture of the two phases γ iron and Fe_3C. In steels far removed from the eutectic composition the troostite is always accompanied by visible pro-eutectic elements. It is not in structural equilibrium with, but furnishes the same constituent elements as pearlite.

10. The direct invertible and quasi-reversible solid solution γ iron-carbon → complex $Fe_3C + \alpha$-iron, which characterises, at a falling temperature, the formation of troostite, and as regards continued cooling takes place at about 650°; can, by interrupting a rapid cooling the rate of which is greater than the critical rate of quenching, take place at a lower temperature, and has

been noted at about 400° to 450°. In these circumstances the troostite occurs, after immersion with recalescence, very strongly marked and bulky. It is therefore a sharply defined reaction, whereas the indirect, non-invertible and hence irreversible transformation (which takes place during annealing and gives birth similarly to constituents which in appearance, nature, and staining properties with suitable reagents are analogous, and are described by different authors as troostite, osmondite, and sorbite) takes place at a relatively slow rate.

11. The temperature of 350° appears, as regards carbon steels, to be an upper limit of desirable temperature of immersion in the case of interrupted quenchings or of limited hardness, without causing an appreciable diminution in the hardness beyond that due to the slight annealing which takes place during the second stage of the operation.

APPENDICES.

No. I.—NOTE ON THE INFLUENCE OF THE INTERNAL EVOLUTION OF HEAT ON THE DURATION OF COOLING.

When, in the course of cooling from T_1 to T_0 there occurs, as the result of an internal transformation, a liberation of heat, the duration of the cooling τ, between T_1 and T_0, is increased by an amount $\Delta\tau$. This varies not only with Q, the quantity of heat liberated during the transformation, but also with the point on the temperature scale at which the heat is liberated. For a given quantity of heat Q set free $\Delta\tau$ is larger in proportion as the temperature of transformation is lower. It is easy to verify this by examining a case where the transformation shows itself, on the cooling curve, by a horizontal bend or step.[1] The length Δz of this step is such that

$$\Delta z = \frac{dt}{dz} = \frac{Q}{cP}$$

the time; $\frac{dt}{dz}$ being the rate of cooling at the temperature t of transformation; Q the quantity of heat liberated, and cP the calorific capacity of the body at t.

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[1] Portevin, *Revue de Métallurgie*, 1907, vol. iv. p. 805.

If cP be regarded as practically constant, Δz varies in inverse ratio to $\frac{dt}{dz}$, a rate which decreases with the temperature.

Now Δz is the amount by which the cooling curve is displaced horizontally, owing to the interposition of the step—that is to say, of the thermal transformation. It is therefore equivalent to $\Delta\tau$. Thus, if the transformation be assumed to be complete, that is, if Q is constant at temperatures, $\Delta\tau$ will increase as the temperature t is lowered. If the cooling be assumed to follow Newton's law—

$$\frac{dt}{dz} = A\ (t - \theta)$$

where θ is the temperature of the medium in which the cooling takes place.

$\Delta\tau$ then increases in inverse ratio to $t - \theta$, that is, practically in proportion to t, the temperature of transformation, if θ be insignificant as compared with t. It should be understood, of course, that this explanation has been purposely simplified, and that it serves no other purpose than the better to convey the notion of the mechanism of the effect of lowering the temperature on τ, the duration of the cooling. In reality, in the case of steels, cP cannot be regarded as constant in respect to t, besides which the transformation does not take place at a definite temperature but extends over larger or smaller intervals in the temperature scale.

Qualitatively the result is the same; each time that the transformation is relegated to a lower temperature τ increases, and the effect previously described is of sufficient importance for this increase of τ to manifest itself if, owing to the effect of its relegation to lower temperatures, the transformation is incomplete.

No. II.—TEMPERATURE OF THE STARTING OF CRACKS.

No definite information is available as to the temperature at which cracks commence. This arises, on the one hand, from the difficulties of recording temperatures during the course of very rapid coolings, and on the other hand, on the impossibility of noting definitely the exact moment when the crack occurs.

During the course of these experiments very few specimens cracked, some at the ordinary temperature, that is, after quenching was completed, and others during the quenching operation. The samples being cylindrical and the cooling being symmetrical in respect to the axis, the cracks would have this axis as an element of symmetry, hence they were either in a diametrical direction, that is, in a direction following a plane passing through the axis, or perpendicular to that axis.

This is what occurred in the case of the cylinder shown in No. 12, Plate XXXV., which in the course of quenching cracked along a section midway, the crack being evidently started in the little circular nick at this position, which was made in each of the specimens with the very object of helping to fracture the sample after quenching. Ultimately the upper half of the cylinder fractured spontaneously in the cold, along a diametrical plane.

The first crack went completely to the centre, to the spot where the thermo-junction of the couple was, whence arose the sudden cooling marked on the curve by a vertical bend at a temperature of 70°. We can therefore know, in regard to this sample, the exact time and temperature of the starting of the cracks; one at 70° and the other at 10°, that is to say, at a very low temperature.

This can easily be explained, but affords a direct experimental proof of what might have been foreseen. It shows the usefulness of arresting the quenching and removing the hot samples from the quenching bath, if they be liable to flaws.

In regard to the other cracked samples, the cracks occurred in the interiors or externally without reaching the locality of the couple, hence the temperature of their starting points is not known.

No. III.—EXPERIMENTS ON SPECIAL STEELS.

To investigate the influence of the special metals, manganese, silicon, chromium, tungsten, &c., on the critical rate of quenching would have led the authors too far, particularly as the question had not been fully exhausted as regards carbon steels, despite the numerous experiments made. Besides this, the authors had only a limited time at their disposal, while their means of investigation were reduced to the simplest. They made, however, a very small number of experiments on certain special steels, the results of which are briefly given.

The steels experimented with had the following chemical composition :

No.	Carbon per Cent.	Manganese per Cent.	Silicon per Cent.	Other Elements per Cent.
4N2	0·21	0·02	0·03	1·97 nickel
4N5	0·20	0·02	0·04	4·90 "
9N2	0·80	0·11	0·10	2·20 "
8M2	0·93	1·97	1·03	...
8C2	0·89	0·10	0·28	2·14 chromium
8W2	0·80	0·05	0·06	2·75 tungsten

The samples, in cylinders 18 mms. in diameter, were quenched at about 800° in the case of low percentages of carbon (4N2 and 4N5) at about 725° to 750° in the case of steels containing about 0·80 per cent. of carbon. The curves of average cooling are shown in Figs. 51 and 52.

The curves of steels 9N2, 8M2, and 8C2 (No. 3 of Fig. 51, and Nos. 2 and 3 of Fig. 52) show no Ar′ point ; they have undergone hard martensitic quenching, which was easily to have been foreseen. On the other hand, the steel 8W2 affords a curve (No. 1, Fig. 52) with the Ar′ anomaly at about 600°. The steels with low carbon (4N2 and 4N5) have the anomalies on their curves at 650° and 400° respectively (1 and 2, Fig. 51). The lowness of the latter is explained by the well-known influence of nickel on the transformation points.

The authors would not, of course, draw any general conclusions whatever from these tests, which are only quoted here to afford information. As they considered it advisable to carry out over 250 tests as regards carbon steels, it may readily be imagined that many more would be required before the effect of a given special element could be ascertained definitely, seeing that this would introduce yet another variable into the problem.

No. IV.—INFLUENCE OF PRESSURE ON THE FORMATION OF TROOSTITE.

As the transformation of the solid solution γ-iron + carbon to $\rightarrow$ α-iron + Fe_3C is accompanied by an increase in volume, any increase in pressure will tend to facilitate it. Now, from the commencement of cooling and as the result of the initial contraction of peripheral zones, the centre portions of a piece of steel should be under compression, which would facilitate the birth of troostite at high temperature.

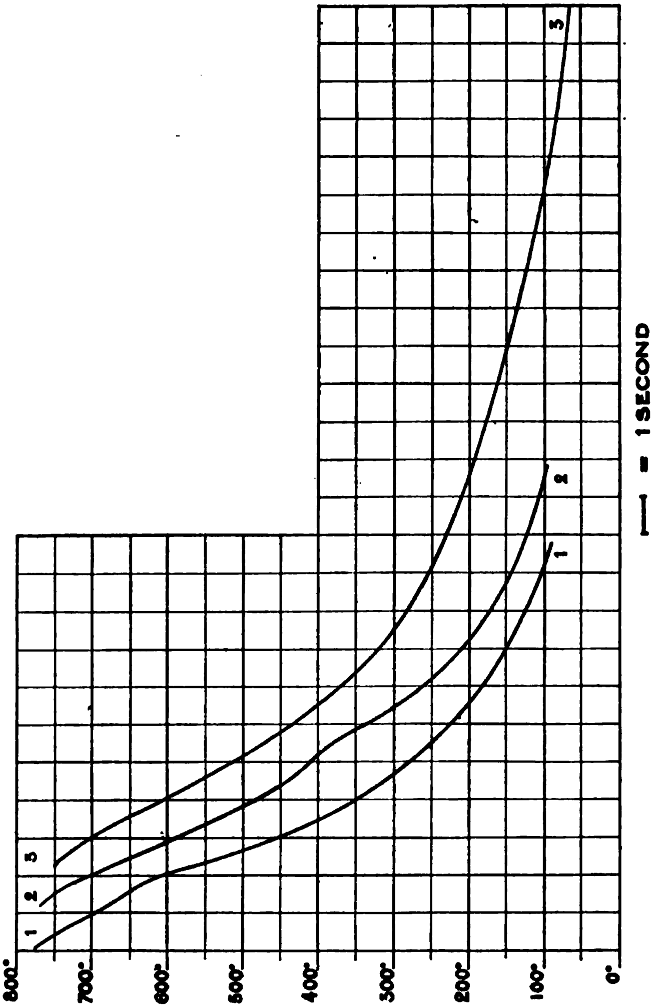

FIG. 51.—Cooling Curves at the Centres of Cylinders 18 mm. in Diameter, in various Nickel Steels quenched in water:

Curve No. 1: steel 4 N 2 (0·2 per cent. carbon—2 per cent. nickel)
" No. 2: " 4 N 5 (0·2 " " 5 " ")
" No. 3: " 9 N 2 (0·8 " " 2 " ")

On the other hand, the formation of martensite, starting from the solid γ-iron solution, is similarly accompanied by an increase in the volume. In the final periods of cooling it is the outside zones which are under compression, and this favours the production of this constituent at low temperatures. The authors have no data as to the amount, distribution, direction, and variation of the internal stresses in a piece of steel in the course of cooling, and it is needful to guard against hypotheses which depend on the effect of an immeasurable quantity, as there is always a temptation to attribute to it values favouring *a priori* conceptions, and

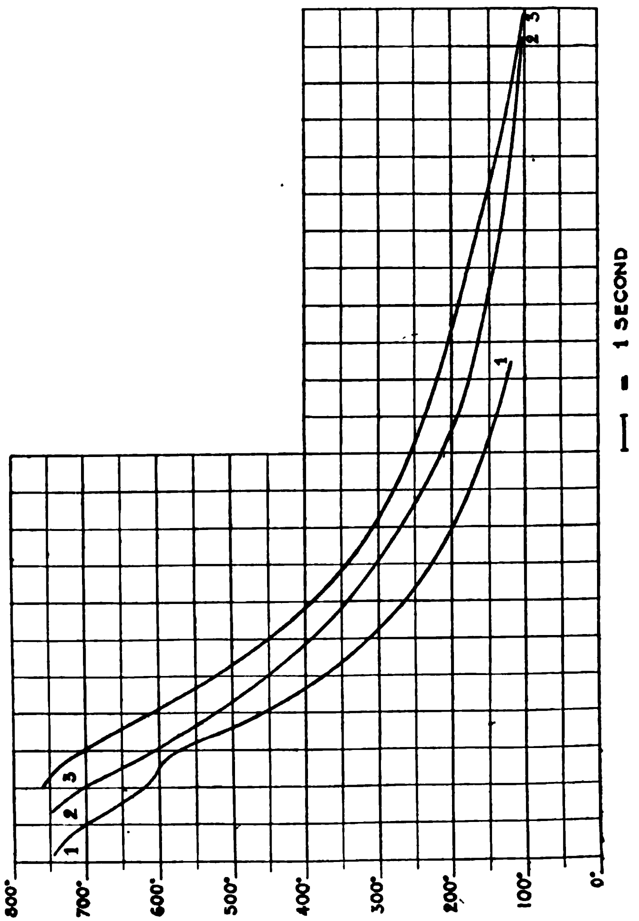

Fig. 52.—Cooling Curves at the Centres of Cylinders 18 mm. in Diameter, in various Special Steels quenched in water:

Curve No. 1: steel 8 W 2 (0·8 per cent. carbon—2·7 per cent. tungsten)
" No. 2: " 8 M 2 (0·9 " " 2 " manganese)
" No. 3: " 8 C 2 (0·9 " " 2 " chromium)

to give to a *petitio principii* the appearance of a demonstration. It is from such methods of reasoning that the interminable disputes relating to theories of quenching have arisen, which have no likelihood of ending so long as they rest on such foundations.

Nevertheless, if these considerations as to pressure really do intervene, it should follow that the critical rate of quenching should be higher in samples with small diameters than in others, and that this would afford a method of obtaining evidence as to part played by pressure, by comparing the critical rates of quenching of samples of different diameters. It would thus be necessary to vary the rates of cooling by altering the external conditions.

Henceforth, however, some data is available in this connection, by comparing the results of the authors' experiments with the particulars given by Mr. Chevenard[1] as to the quenching of fine wires of 0·23 mm. This quenching of fine wires in a gaseous atmosphere (hydrogen and nitrogen) was followed by dilatometrical methods of investigation which show the Ar″ transformation at low temperatures leading to the birth of martensite, much more clearly than the plotting of cooling curves. On the other hand, the temperatures, and consequently the law of cooling, can only be known by assuming the identity at the commencement of the phenomenon of transformation of the temperatures of the steel wires experimented on, and those of a wire of *baros* of the same diameter (alloy of nickel and chromium: chromium = 10 per cent.) cooling in the same medium. Given the conditions of comparability laws of cooling noted in the first part of this paper, and the important accidental perturbations which the authors have observed in these laws when samples of very small diameters are concerned (about 8 mms.), it may be imagined that, even in the case of cooling in a gaseous atmosphere, the comparability is in danger of not being as perfect as it might be, *a priori* supposed, when diameters of only a fraction of a millimetre are in question.

However this may be, it will be seen from the results given by Mr. Chevenard on a steel containing 0·86 per cent. of carbon and 0·15 per cent. of manganese, in wires of 0·32 mm. diameter, that the critical rate of quenching exceeds 700° seconds at 750°, when the initial quenching temperature is in the neighbourhood of

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[1] *Comptes Rendus*, 1917, vol. 165, p. 59.

750°. If reference be made to the present authors' experimental results on steel with 0·81 per cent. of carbon and 0·21 per cent. of manganese, it will be found that, on the other hand, with cylinders of 20 mms. in diameter the critical rate of quenching is lower in these conditions than 100° seconds at 750°.

The divergence is too great to be imputed to differences in the comparability of the experiments, and we are driven to attribute to the pressure an effective influence on the formation of the troostite, although it is only by quantitative numerical deductions, and not by qualitative and *a priori* considerations, that it would be possible to say exactly what that influence is.

CORRESPONDENCE.

Dr. A. McCance (Glasgow) wrote expressing his warm admiration of Messrs. Portevin and Garvin's brilliant research. The difficulties of carrying out cooling curve records of quickly cooling steels could only be appreciated by those who had tried similar experiments, and the numerous results contained in the authors' paper testified to the success with which they had overcome the possible errors. The very full details given in the paper of the apparatus and the method of experiment left little doubt that the recorded curves for the larger diameters were very close to the actual variations in temperature at the centre of the specimens, but he hoped at some later date to analyse theoretically the ability of the couple to follow rapid variations in temperature and to find, if possible, the limitations of the method, since in existing circumstances the assumption had to be made that thermal lag was negligible. There was in consequence not the same accuracy possible for the curves for the smaller diameters, though what the amount of the probable error was could not be stated.

In measuring the cooling time and drawing conclusions from the results, it should not be forgotten that the calculated curve did not take account of thermal perturbations due to molecular changes, and that steel was not the best material to use for comparisons. It would be of great value if the authors could give complete curves for gradually increasing diameters for bars of a metal like copper or ferro-nickel which gave smooth cooling curves, and then compare the time rates for different dimensions. An insight could then be obtained into the action of the cooling liquid and the relative importance of latent heat, viscosity, &c., in the cooling action. It was owing to the variation of the latter that he (Dr. McCance) did not favour the cooling time being measured by the time taken to fall from 700° to 200° C., since the range was too large for comparison purposes and the law of cooling was not the same at the beginning and the end. In the initial stages of quenching the surface was automatically kept at the boiling temperature of the liquid in which the specimen was immersed, but when the flow of heat was insufficient to maintain this temperature, heat was abstracted from the surface by convection currents only, and the rate of cooling of the specimen was in consequence greatly retarded. The rate of cooling was altered from the one set of conditions to the other quite gradually of course, but where the change began was entirely unknown. In addition, thermal change points in the material had a very pronounced influence on the cooling rate, as Messrs. Portevin and Garvin had so clearly shown, so that the range 700° to 200° could not be used to demonstrate the variation in cooling rate with the dimensions of the bars. For comparison purposes the velocity of cooling in degrees per second at some specified temperature (preferably 700° C. for steel) was much more suitable and accurate. Only when such figures were available could the law connecting the rate of cooling and the diameter be found out.

He (Dr. McCance) thought Messrs. Portevin and Garvin did not correctly state his attitude with regard to the calculated cooling curves. He had really endeavoured to show that such curves could be calculated in specific instances, and by using that knowledge he had proved that qualitative deductions based on Fourier's theory of heat were actually borne out by the experimental results. Such curves were calculated for rods in which the cooling effect of the ends was neglected, and in his own experiments the dimensions of the rods were intentionally chosen so that that could be done, and the diameter, 9 millimetres, was so near that of 6·5 millimetres employed by Benedicks, that no great error arose in altering the calculation to suit the different variables. The results, he thought, justified the means. For instance, taking the critical velocity of cooling, by applying his formula to the bars of 0·86 per cent. carbon steel with 0·07 per cent. manganese, the velocity at 700° C. came out between 168° and 180° per second,[1] the mean being 174°. Now from Fig. 31 in the authors' paper the critical rate for a steel with 1·07 per cent. carbon and 0·08 per cent. manganese was as near as could be measured 175° C. per second. Perhaps Messrs. Portevin and Garvin, however, would be good enough to give the exact figures from their original curves. The closeness of those results was striking proof that the formula which he (Dr. McCance) gave was correct within the limits of its application.

Again, taking Fig. 18 and calculating for a value of β of 0·0824, the times and temperatures, using 700° as zero time, calculated and observed were as follows:

Time. Secs.	Portevin and Garvin, Fig. 18.	Calculated 0·0824.
0	700	700
2	530	532
4	390	395
6	300	306
8	240	240
10	190	190
12	160	162

Again it would be seen that the theoretical basis was justified. The effect of the short ratio of length to diameter had not been taken into account, but it had not really much effect in that case since the correction amounted only to about 5° in the neighbourhood of 300° and grew less at each end of the curve.

It might be as well to give in that connection the general instance of a short rod of length $2l$ and diameter $2a$ heated to any temperature $f(r, \theta, z)$ and plunged into a liquid which kept the sides and ends everywhere at zero temperature. The temperature at any point was then given by the expression

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[1] *Journal of the Iron and Steel Institute*, 1916, No. I. p. 151.

$$T = \sum_{\mu} \sum_{n=0}^{\infty} \sum_{m=0}^{\infty} e^{-\kappa\left(\mu^2 + \frac{m^2 \pi^2}{9l^2}\right)} J_n(\mu r) \, . \, \text{Sin} \frac{m\pi}{2l}(z + l) \, . \, A_{\mu mn} \text{Cos}\, n\theta + B_{\mu mn} \, . \, \sin n\theta$$

where the coefficient $A_{\mu mn}$ was given by

$$A_{\mu mn} = \frac{2 \int_0^a J_n(\mu r)\, dr \int_{-l}^{+l} \text{Sin} \frac{m\pi}{2l}(z + l)\, dz \int_{-\pi}^{+\pi} \text{Cos}\, n\theta \, f(r, \theta, x)\, d\theta}{\pi^2 a^2 l \left(J_{n+1}(\mu a)\right)^2}$$

and a similar expression held good for $B_{\mu mn}$ with sin $n\theta$ replacing cos $n\theta$. J_n was the bessel function of the Nth order.

Many would be relieved to know that that simplified into

$$\frac{T}{\theta} = X \, . \, \frac{4}{\pi} \left\{ 10^{-\gamma t} - \frac{1}{3} \, . \, 10^{-9\gamma t} + \frac{1}{5} \, 10^{-25\gamma t} - \text{etc.} \right\}$$

in which X was the function given on p. 498 in the paper, and

$$\gamma = 0{\cdot}427 \, . \, \frac{a^2}{l^2} \, . \, \beta$$

That formula made a slight difference which had the effect of shortening the cooling time for the larger diameters so that they were no longer proportional to d^2 but to a power slightly less than 2. It also prevented the curves being derived from one parent curve, but they could be derived from two parent curves by expressing the second portion as a coefficient of unity.

On taking the cooling velocity at 700° from Fig. 39 of the authors' paper by drawing a tangent to the curves and plotting the result as the inverse of that against the diameter, the curve Fig. A showed that the cooling velocity was not proportional to the diameter as was the cooling time of the authors' 700° to 200°, but that it was proportional to some power of the diameter greater than 1 but less than 2. It was, as he had previously stated, probable that the recorded curves for the quicker rates of cooling were to some extent influenced by thermal lag.

Turning to the metallurgical results he was glad to see that everything Messrs. Portevin and Garvin had found was in keeping with the views which he had expressed in 1914 and still held as his considered opinion. The authors had proved in the most convincing manner what he (Dr. McCance) had only been able to surmise, namely that the change from gamma to alpha iron could take place independently of the carbon change when the rate of cooling exceeded a certain critical value which was different for steels of different composition. That was the beginning of the end of the mystery of steel hardening and conclusions would undoubtedly follow quickly. It might interest the authors to know that work which he (Dr. McCance) had commenced in continuation of his own work on hardening, which had been laid aside during the last five years owing to the pressure of other duties, went to show that, on tempering, a similar splitting up took place, and that the gamma iron in martensite changed at ordinary temperatures to alpha iron at a rate about ten times as fast as the rate of change of the carbon from its state of solution. Both changes were purely physical changes whose variation with temperature could be calculated exactly. The most important corollary was that the carbon could be very largely out of solution without the steel losing its hardness. It was the final demonstration which confirmed that the hardness was a property of the iron itself, and that the carbon was only the means of bringing that property into existence. He hoped at a later date to publish those results. In conclusion, he congratulated Messrs. Portevin and Garvin on their paper, which was one of the most important contributions to the theory of hardening action which had yet been published.

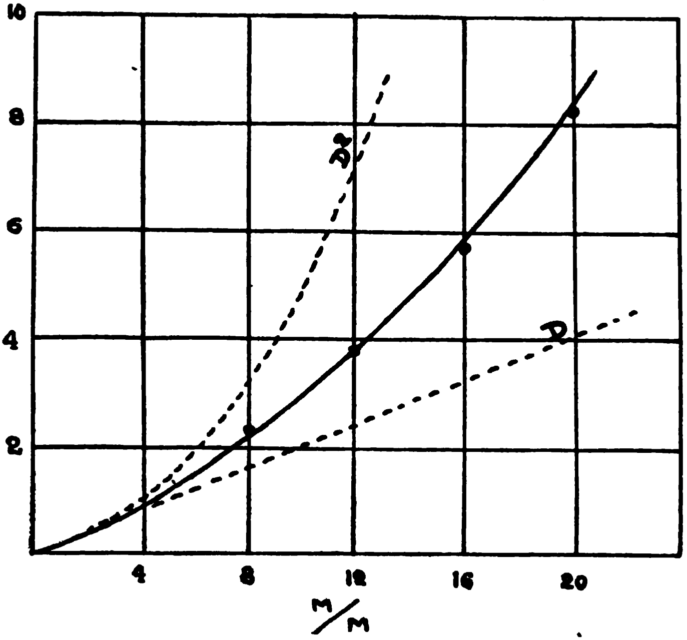

FIG. A.

GRAPHITISATION IN IRON-CARBON ALLOYS.[1]

BY KUNIICHI TAWARA AND GENSHICHI ASAHARA (TOKYO UNIVERSITY).

1. INTRODUCTION.

ALTHOUGH the literature of the iron-carbon system is so large, little is known as to the actual mechanism of the formation of graphite in iron-carbon alloys. The following paper is based on experiments undertaken in order to throw, if possible, further light on the subject.

2. EXPERIMENTS.

The presence of impurities, such as silicon, manganese, &c., influences the generation of graphite in iron-carbon alloys. For this reason, charcoal-iron, produced in Western Japan (Tyûgoku) from pure magnetic iron sand, was used in the preparation of the alloys, as it contained practically negligible amounts of impurities, its composition being as follows:

Carbon.	Silicon & SiO_2. Per Cent.	Manganese. Per Cent.	Phosphorus. Per Cent.	Sulphur. Per Cent.	Copper. Per Cent.
0·15	0·08	trace	0·01	0·01	nil

The carbon was irregularly distributed and varied from nil to 0·7 per cent., but the average in a strip of iron was 0·15 per cent. A small quantity of silica was present as slag mechanically contained. Manganese was present only in traces, and no copper was found. About one kilogram of the charcoal-iron was charged in a Morgan's clay crucible together with a certain quantity of hard charcoal (C = 87 per cent.) and heated in a Deville's furnace with blast until it melted, no charcoal remaining on the surface of the melt. The molten alloy was cast in a flat rectangular metallic mould, white pig iron containing nothing but carbon and iron being obtained. About 20 kgs. of the alloy were prepared in separate casts, their carbon content varying between 2·95 per cent. (minimum) and 3·92 per cent. (maximum). One of the casts prepared in this manner, and taken at random, gave on analysis 0·10 per cent. of silicon, an amount which can safely be disregarded in considering the results.

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[1] This paper has been condensed from the original.

As it was thought that an increase of silicon might occur through the use of the clay crucibles, and so affect the results, these samples were specially analysed, and it was found that the percentage of silicon was invariably lower after melting, and might be regarded as a negligible constant.

In preparing the alloys the temperature which the molten metal reached during the heating (the "highest temperature") and the temperature at which the metal was cast (the "casting temperature") were measured respectively. Measurements by the Fery patent pyrometer having proved difficult, a thermocouple was used, protected by a silica tube.

The highest temperature was measured by dipping the thermo-element into the molten metal, which was then allowed to cool, the thermo-element remaining in position until the desired casting temperature was reached.

The moulds used in the experiments were, in most cases, of fireclay mixed with coarsely powdered crucible material, and were of the shape of an equilateral triangular prism, the side of the equilateral triangle being 1½ inches long. The other dimensions are given in Fig. 1.

In all cases the mould had previously been heated in a concentric gas-jet crucible furnace up to a certain temperature before the molten metal was cast in it. The temperature was measured with a thermocouple which was inserted into a hole (*a*) in the mould.

The ingot, after this treating, was slowly cooled in the furnace or quenched in water. It was then examined microscopically and chemically.

The arrangement adopted is sketched in Fig. 2.

The average temperature throughout the experiment is cited as the "temperature of the mould" for the sake of convenience, where necessary.

The table on p. 569 shows the conditions of the experiments. The carbon was determined by the wet combustion method (chromic acid method). Graphite in the ingots, if present, was very liable to be lost in the preparation of the samples for analyses, so that all due care was taken, in sampling, to avoid this.

In those cases where graphite appeared in certain confined portions distributed in the ingots, the analysis of graphite was not carried out, as the result would have little meaning. Such samples were only examined microscopically.

It was at first intended that the percentage of carbon in the final ingots should be 3 per cent., 3·5 per cent., and 4 per cent. in round numbers. This, however, was not always practicable, though the values are fairly near to those sought. All the samples were analysed for carbon and silicon, and in one case, chosen at random, the phosphorus, sulphur, copper, and manganese were also estimated. The result was as follows:

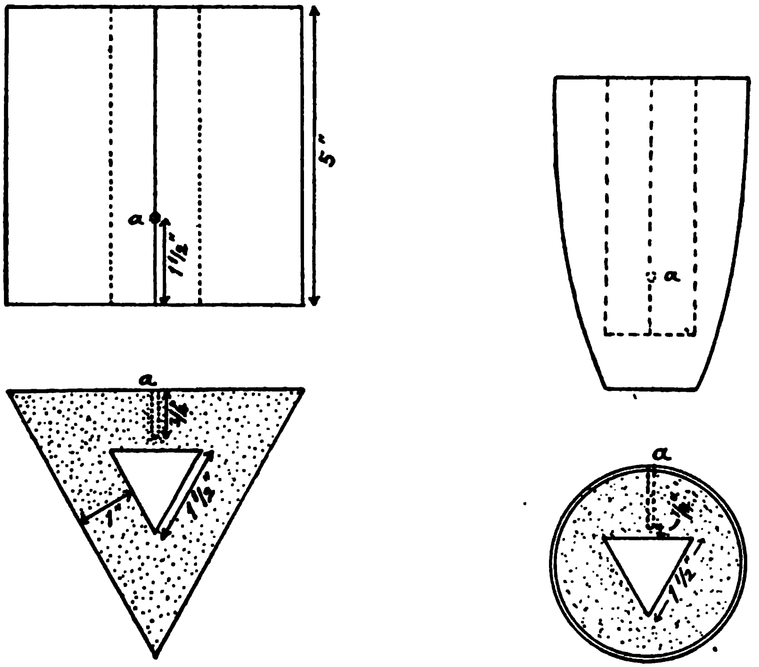

Fig. 1.—Form of Ingot and Mould Adopted.

Phosphorus. Per Cent.	Sulphur. Per Cent.	Manganese. Per Cent.	Copper. Per Cent.
0·06	0·09	trace	0·0

No practical effect may be expected from these minute quantities.

The experiments were so devised that only one factor differed in each case, namely, the six variables with regard to graphitisation : (1) The chemical composition of the alloys ; (2) the " highest

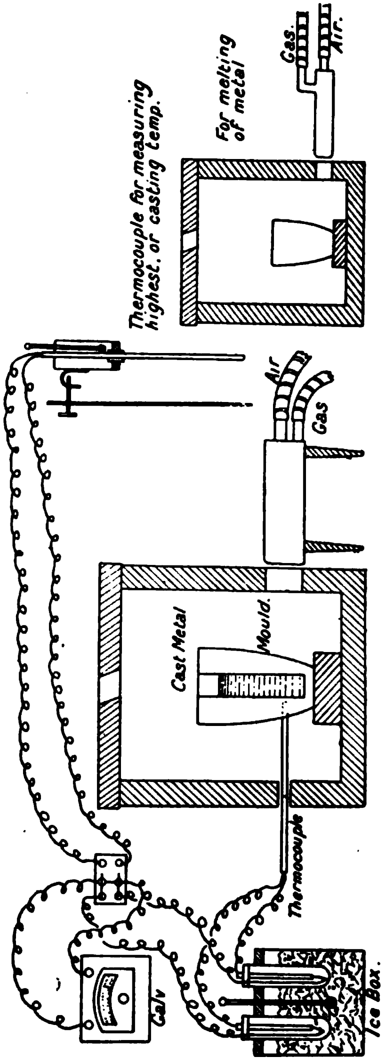

FIG. 2.—Arrangement of Apparatus.

temperature " ; (3) the " casting temperature " ; (4) the " temperature of the mould " ; (5) the " time " ; and (6) the " mode of cooling " of the reguli. The effects on the microscopical constituents and structure due to each of those factors were as follows:

1. *Chemical Composition of the Alloys.*—It depends largely, of course, upon the chemical composition, whether graphitisation occurs or not. The material used in the experiments containing practically nothing but iron and carbon, graphitisation, if present, is certainly not caused by such impurities as silicon, &c. Indeed, the graphitisation in the experiments is almost entirely due to the slow cooling of the metal at or near its solidification point. Graphite is always to be seen in an ingot which was slowly cooled, even when there is practically no silicon, which was formerly supposed to be necessary in graphitisation.

No. of Experiment.	Highest Temperature.	Casting Temperature.	Temperature of the Mould.	Time.	Mode of Cooling.	Chemical Composition.			Microscopic Constituents.
						Total Carbon.	Graphite Carbon.	Silicon.	
	Degrees C.	Degrees C.	Degrees C.	Hours.		Per Cent	Per Cent	Per Cent	
1	1287	1237	1000	1½	Slow	3·20	*	0·02	G.C.P.(L.).
2	1274	1233	1100	1½	”	...	*	0·05	G.C.P.
3	1315	1266	1100	1½	”	...	*	...	G.C.P.
4	1301	1251	1100	1⅙	”	3·08	*	0·03	G.C.P.
5	1355	1330	1100	1½	”	3·93	2·18	0·05	G.C.P.
6	1336	1328	1100	1½	”	3·45	1·53	0·04	G.C.P.
7	1333	1325	1100	1½	”	2·48	*	0·02	G.C.P. (L.).
8	1409	1388	1100	1½	”	2·18	*	0·05	G.C.P.
9	1436 (for each ½ hr.)	1329	1100	1½	”	3·36	1·50	0·06	G.C.P.
10	1356	1323	1100	3	Very slow	3·25	1·64	0·01	G.C.P.
11	1402	1270	1100	0	Quenched in water	3·10	Nil	0·05	Ar.L.
13	1361	1328	1100	½	Slow	3·23	1·60	0·05	G.C.P.
14	1393	1327	1100	1½	Quenched in water	3·42	1·26	0·02	M.G.
15	1346	1325	1100	...	Slow	3·65	2·14	0·03	G.C.P.
18	1416	1399	1100	1½	”	3·34	1·73	0·03	G.C.P.
20	1357	1316	1000	8	Quenched in water	3·63	*	0·02	Ar.C.L.G.
21	1334	1318	1000	½	”	3·60	*	0·01	Ar.C.L.G.
22	1325	1317	1100	½	”	3·58	*	0·02	Ar.L.G.
23	1363	1322	900	7½	”	3·42	Nil	0·03	Ar.L.
24	1339	1314	1122–1126	1½	”	3·40	Nil	0·03	Ar.L.
27	1335	1323	50 (metre mould)	(Chilled casting)		3·61	Nil	0·01	Ar.L.

* Refers to partial graphitisation, *i.e.* the presence of graphite in certain parts.
G. = Graphite. C. = Cementite. P. = Pearlite. L. = Ledeburite. Ar. = Austenite (resolved).
M. = Martensite.

No. 5 and No. 6 underwent nearly the same heat treatments, and differed only in carbon contents. The percentages of carbon in these two alloys were found to be 3·93 per cent. and 3·45 per cent. respectively. The microscopical structures of the two did not differ greatly. No. 5 contained more graphite (2·18 per cent.) than No. 6 (1·53 per cent.). So far as the present results are concerned, there was no marked effect upon the structure by the change in carbon content within certain limits (0·5 per cent. fluctuation).

No. 7 was also carried out under the same experimental conditions as the above, only the percentage of carbon being modified (2·48 per cent). Graphite was present in very small quantity and in a certain limited space. The mass was very much like white iron.

It might be assumed from these examples that the quantity of graphite (under the same conditions) depends on the carbon content of the alloy, the quantity in No. 5 being considerably greater than in No. 7 even when compared with No. 6. This is explained by assuming that the excess carbon over 2 per cent. (which is the limit of saturation of primary austenite) crystallised out as graphite. On the other hand, the above conclusion might be expected from the equilibrium diagram of the FeC system. The carbon percentage of any alloy in the experiments is between 2 per cent. and 4 per cent., so that the constituents which appear at the time of solidification are primary austenite and graphite, and no other new constituent is introduced. Moreover, the increase in carbon content means, in the equilibrium diagram, the approach to the eutectic freezing point of primary austenite and graphite. Accordingly, more graphite should be produced out of the carbon which is in excess of the limit of saturation of austenite with carbon. It is, of course, understood that the above remark with regard to the quantity of graphite only applies when the conditions of the experiments are similar (and favourable for graphitisation), except as regards content of carbon.

In No. 8 the highest temperature and the casting temperature are higher than in the other three cases, besides which the carbon is as low as 2·18 per cent. Graphite occurred in certain parts of the ingot. In this case it might be necessary to raise the casting temperature so as to make the case comparable with the others, because the percentage of carbon is smaller and the solidifying temperature is consequently higher. However, this is not strictly the case in No. 8, although it is evident that graphitisation can take place even when the content in carbon is as small as 2·18 per cent.

It may be assumed, therefore, that the amount of carbon in the alloys, when ranging from 2 per cent. to 4 per cent., is not a decisive factor in graphitisation. It causes no change in the species of microscopical constituents; but it influences the quantity of graphite produced.

2. *The Effect of the "Highest Temperature."*—

No. of Experiment.	Per Cent. Carbon.	Highest Temp.	Casting Temp.	Temp. of Mould.	Time. Hours.	Mode of Cooling.
6	3·45	1336°	1328°	1100°	1½	Slow cooling
9	3·36	1436°	1329°	1100°	1½	„

It is in general true that some grains or nuclei are necessary when a new phase appears in the existing phase or phases. There must, therefore, necessarily exist graphite grains when graphite is produced in molten or solidified metal, though the mechanism of its development is not known.

Wüst and Goerens and others assume that graphite is a decomposition product of cementite in solid phase, and that the decomposition may take place very shortly after the solidification of the alloy. However, we may assume the existence of the grains of graphite in a molten metal, from which graphite crystals start their development, possibly at the eutectic point. Those grains may result from the dissociation of cementite in the molten state, and if so they will be affected by a temperature change, and consequently graphitisation may be influenced.

In No. 9 the molten metal was kept at 1436° C. for about half an hour after it had attained this "highest temperature," while in other cases the "highest temperature" was not maintained for so long a time.

On comparing No. 6 with No. 9, no perceptible difference could be found in their structures.

The result of the experiments shows that the "highest temperature," *i.e.* the maximum temperature which the molten metal has reached, has apparently no effect on graphitisation. In the experiments, therefore, no special precautions were taken respecting this factor, which varied within a certain range of temperatures.

3. *The Effect of the Casting Temperature.*—

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp.	Mould.	Time. Hours.	Mode of Cooling.
6	3·45	1336	1328	1100	1½	Slow cooling
18	3·34	1416	1399	1100	1½	„

The temperature difference between the casting temperature and the temperature of the mould is the main factor which determines the solidifying velocity of a molten metal and the cooling velocity of the solidified mass, and it often controls the microscopical structure of alloys.

The above experiments were carried out to ascertain the effect of the casting temperature. The temperature of the two moulds was 1100° C., and the casting temperature in No. 18 was 71° C. higher than in No. 6. The slight differences both in the chemical compositions and in the highest temperatures are quite negligible, as shown by the results.

Microscopically, there was no marked difference in the structures. The authors' resources did not permit of higher casting temperatures being tried, which might have given very interesting data as to graphitisation.

The recorded modification in the casting temperature did not cause any difference in the structures.

4. *The Effect of the Temperature of the Mould.*—The temperature of a mould partly defines, as well as the casting temperature, the solidifying and cooling velocities of a molten metal. Rather higher temperatures, such as those chosen in the experiments, favour graphitisation, as they result in slow cooling.

(*a*)

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hour.	Mode of Cooling.
21	3·60	1334	1318	1000	½	Water quenching
22	3·58	1325	1317	1100	½	„

In these cases ingot metals were rapidly quenched in water. In both cases graphite was seen in certain parts in the mass, showing that graphitisation can take place at 1000° C. as well as at 1100° C. These graphite flakes were not produced by the slow cooling down from these temperatures, as the mass was quenched at once.

(*b*)

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hours.	Mode of Cooling.
14	3·42	1393	1327	1100	1½	Water quenching.
24	3·40	1339	1314	1125–1128	1½	,,

In No. 24 an effort was made to keep the temperature of the mould as near the eutectic temperature as possible. There is, however, some doubt whether the mass assumes the proper structure corresponding to the conditions described or not. There is no graphite at all in No. 24, while there is plenty of it in No. 14. This is probably due to keeping the mould at 1125°–1128° for 1½ hours, so that the eutectic, being unable to solidify at all, could not deposit graphite.

(*c*)

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hours.	Mode of Cooling.
20	3·63	1357	1316	1000	8	Water quenching
23	3·42	1363	1322	900	7⅓	,,

In these cases the temperatures of the moulds were kept at 1000° C. and 900° C. respectively for a rather long time. The "time" in No. 23 was less than eight hours owing to an accident. This relatively small difference in the "time" may be, however, overlooked so far as graphitisation is concerned.

No. 23 did not contain even a trace of graphite, while No. 20 did. It is accordingly shown that graphitisation cannot take place at such a temperature as 900° C., even when maintained for 7⅓ hours. It is questionable whether graphitisation can take place by more prolonged annealing at that temperature or not.

(*d*) In summarising the three cases, it is shown that the temperature of the mould has some effect on graphitisation. Graphite was not found in the case of 900° C. A temperature 1100° C. is the most favourable of the three.

5. *The Effect of the "Time" of Annealing.*—The "time" of annealing means, in other words, the rate of cooling of a mass in the earlier stage.

(*a*)

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hours.	Mode of Cooling.
10	3·25	1356	1323	1100	3	Slow cooling
6	3·45	1336	1328	1100	1½	”
13	3·23	1361	1328	1100	½	”
15	3·65	1346	1325	1100	0	”

In these four cases, the “ time ” is the only factor modified, other conditions remaining the same.

No considerable microscopic change could be detected. Homogeneous graphitisation had taken place in every case. From this fact, it may be concluded that when the temperature of the mould is 1100° C. there is no appreciable effect on graphitisation, whether the cooling of the metal begins directly after the casting or after three hours' annealing at the temperature.

(*b*)

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hours.	Mode of Cooling.
14	3·42	1393	1327	1100	1½	Water quenching
22	3·58	1325	1317	1100	½	”

In No. 14 the microstructure was quite homogeneous throughout, and there was even distribution of graphite. On the other hand, graphitisation was not complete in No. 22, where graphite existed only in certain limited parts.

In these cases, therefore, the “ time ” seems to have exercised an effect apparently on graphitisation and gives a discordant conclusion with that of (*a*). The only accountable cause is the difference of the mode of cooling in these two experiments. This case will be considered later on.

(*c*)

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hours.	Mode of Cooling.
20	3·63	1357	1316	1000	8	Water quenching
21	3·60	1334	1318	1000	½	”

In these examples graphite existed only in certain limited spots in both masses, and the structures are quite similar.

So far as graphitisation is concerned, the “ time ” seems to have no effect on the completeness. The incomplete graphitisation due to water quenching will be considered later.

It must be concluded from (*a*) and (*c*) that the “ time ” alone cannot exercise any appreciable effect on graphitisation, while (*b*) leads to an opposite conclusion. This discrepancy may be explained if we assume the minimum length of the "time" necessary for graphitisation to be, say $1\frac{1}{2}$ hours, and also the favourable effect of the slow cooling. The latter will be discussed later in No. 6.

6. *The Effect of the Mode of Cooling.*—

(*a*)

No. of Experiment	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hours.	Mode of Cooling.
6	3·45	1336	1328	1100	$1\frac{1}{2}$	*Slow cooling.*
14	3·42	1393	1327	1100	$1\frac{1}{2}$	*Water quenching.*

Graphite flakes were distributed throughout the mass in both cases, and their structural arrangement was similar microscopically. In No. 6 the ground mass consisted of pearlite and cementite (needle), while that in No. 14 was largely martensite.

This shows that the difference of slow cooling and water quenching causes a change simply in the method of the decomposition of primary austenite, which constitutes the ground mass of the solidified metal, and is no serious factor in graphitisation. In other words, it shows that graphite crystals are not likely to be produced in the later stage of cooling.

(*b*)

No. of Experiment.	Per Cent. Carbon.	Highest Temp. Degrees.	Casting Temp. Degrees.	Temp. of Mould. Degrees.	Time. Hour.	Mode of Cooling.
13	3·23	1361	1328	1100	$\frac{1}{2}$	*Slow cooling.*
22	3·58	1325	1317	1100	$\frac{1}{2}$	*Water quenching.*

In No. 13 the distribution of graphite was homogeneous throughout, which was not the case in No. 22.

It has been shown in No. 5 (*a*) that No. 13 and No. 6 are similar with regard to graphite. While No. 13 contains much graphite, it is open to question that No. 22 has a considerable amount of ledeburite, *i.e.* a small quantity of graphite in certain limited parts.

On reviewing all those cases where the metal was quenched rapidly in water, we find that there prevails incomplete, limited graphitisation except in the case of No. 14. The quenching seems to prevent further graphitisation, *i.e.* further decomposition of cementite at the later stage (admitting for the present the decomposition theory of graphitisation). Slow cooling, on the contrary, results in complete graphitisation. However, No. 14 shows that a sufficiently high temperature of the mould and a sufficient " time " will give complete graphitisation even when quenching takes place.

If we consider the results of No. 6 together with those of No. 5, it may be concluded that graphitisation must take place at a certain early stage of cooling of the metal, covering some length of time, and is, of course, favoured by higher temperature. The length of " time " must be at least 1½ hours (strictly speaking, longer than ½ hour) in order to get homogeneous graphitisation, and the quenching after a shorter " time " than this will therefore result in partial graphitisation. The slow cooling in the present experiment may have, in some cases, served to increase the " time " (though this is not definitely certain), thus helping graphitisation in those cases where the " time " did not amount to that required length.

It must be noted that the above remark holds good when the temperature of the mould is 1100° C., but is not true at 1000° and 900° C. However, it is already known that the temperature 1100° is more favourable to graphitisation than the other.

If this be the case, it is quite inconsistent to assume that the slow cooling (especially when it follows after a shorter " time "), can favour graphitisation, notwithstanding that the temperature is steadily falling below those temperatures, such as 1000° and 900° C.

So far as their present experiments are concerned, the authors are inclined to take into consideration the effect of internal stresses in the mass of iron, induced through quick cooling, on graphitisation, but it needs further investigation to deduce any definite conclusion.

The Authors' Theory as to Graphitisation.—Graphite crystals are always contained in an austenite mass (resolved) when they are directly produced by the slow cooling of an alloy. They are not necessarily to be ascribed to the decomposition of the eutectic cementite. The austenite areas, in which graphite crystals are present, are intimately associated with the austenite islets which are scattered in the eutectic. They may not differ much in chemical compositions. As the austenite islets are, without doubt, the primary products from the molten alloy, the austenite beds are also supposed to be the product within a similar period, *i.e.* they may appear side by side with graphite crystals at the eutectic point. This view will not meet any serious opposition or present any difficulty in the explanation of the facts. The following hypothesis may well serve to explain the known facts.

In general, when two metals form a compound and mix with each other to form one homogeneous liquid phase when molten, the fusion curve of the system shows a maximum at the point corresponding with the compound. At this point, therefore, $\frac{d\,(\text{temp.})}{d\,(\text{conc.})} = 0$; *i.e.* the melting point of the compound is not affected by the addition of a small quantity of either of the component metals to the molten alloy. This is explained by assuming a certain amount of dissociation of the compound into the atoms of both the component metals (when it is in molten state). There are, therefore, already a certain number of the component atoms, so that a slight addition to them from outside will not affect the dissociation of the compound. The melting point, therefore, remains unchanged.

It is generally accepted that carbon exists as cementite in the molten iron-carbon alloys. It is probable that cementite, being a compound, may dissociate in the molten state into iron and carbon, even though the amount of the dissociation may be small. These free carbon atoms may serve as the nuclei for the graphitisation when the conditions are favourable.

When an iron-carbon alloy ($2 < \%\ \text{C.} < 4{\cdot}3$) is allowed to cool sufficiently slowly, the primary austenite crystallises out along the liquidus AB and the mother liquor reaches the eutectic composition B (Fig. 3). At this point, when the cooling is sufficiently slow to maintain the equilibrium, graphite will crystallise together with austenite, forming the eutectic, as there are a number of the nuclei already present. The deposition of the dissociated carbon from the molten system will bring about a further dissociation of the molten cementite, as a general rule, in order to re-establish equilibrium. This process is repeated and graphite crystals are developed. On the other hand, the residual molten alloy is diluted all the time by the ferrite, which is the contemporaneous product of the disociation, and finally it will attain the composition A which corresponds with that of saturated austenite (2 per cent. carbon). We have thus a eutectic of graphite and saturated austenite in the final state, and the whole regulus consists only of graphite and austenite, the latter, of course, resolving into pearlite and needle-shaped cementite when cooled.

If the favourable conditions for the solidification of this eutectic of graphite and austenite cease—for example, if the rate of the cooling of the melt becomes greater over a certain range—that process will no longer take place, and cementite will crystallise out of the molten alloy. The separation of cementite at the point B does not represent a true equilibrium; it is a transitional and metastable condition. When the solidification of the alloy is not retarded sufficiently until the whole becomes solid, "mottled" iron will be obtained.

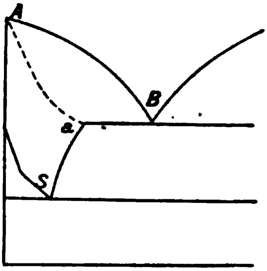

FIG. 3.

In the photomicrographs obtained by the authors, the portions with graphite crystals are regarded as consisting of the primary austenite and the eutectic (of austenite and graphite), the latter filling up the spaces between the "fir-tree form" of the primary austenite. The considerable difference in the dimensions of the constituents between the eutectic of graphite and austenite and the eutectic of cementite and austenite may be considered as the common phenomenon when the alloy is slowly cooled on one hand and quickly cooled on the other hand. In those cases it has been found that there is no ferrite around the graphite crystals, and the latter are intimately surrounded by the resolved austenites needle (cementite + pearlite). On examining the shape of the graphite crystals, it seems rather probable that they are the product of the molten mass, and not the product of the decomposition of cementite in the solid state.

The mode of crystallising the graphite flakes will be well explained in Fig. 4, which shows the separate area of both the

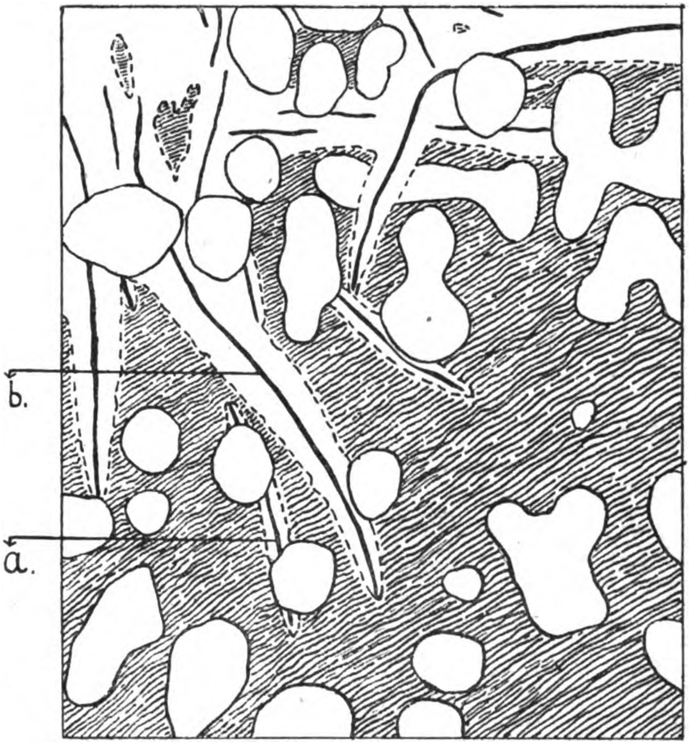

FIG. 4.—Diagram of Sample 22.

primary and secondary austenite, the dotted lines representing the boundaries of the latter, resulted from the deposition of graphite. The graphite flake "*a*" is cut down in its length by two isles of primary austenite, while the graphite "*b*" grows in a long line, just avoiding an island of primary austenite.

The results of the authors' studies agree with Charpy's and Wüst's conclusions. So far, however, as the mechanism of graphitisation is concerned, the present authors are not perfectly in accord with the distinguished investigators referred to. In summarising their own views they would say that in fluid alloys there may exist atoms of free carbon as the dissociation products of dissolved cementite. These may serve as the nuclei for the crystallisation of graphite. Further, the mechanism of the development of graphite flakes is explained in the paper.

In conclusion, they wish to express here their hearty thanks to Mr. G. Aikawa, who kindly provided them with the necessary financial assistance in carrying out the research.

CORRESPONDENCE.

Mr. E. Adamson (Sheffield) wrote congratulating the authors on their endeavour to prove by a series of experiments that graphite was formed in the absence of silicon. He (Mr. Adamson) had proved that on several occasions during the last dozen years or more, and the fact was now more or less accepted. When it came to a question of detail, however, the authors' results clearly demonstrated that in regard to cast iron experiments nothing was certain but uncertainty.

There were three general principles in iron-carbon alloys: 1. The higher the temperature the more carbon the iron could absorb. 2. The longer iron was in contact with carbon at, say, molten temperature, the more carbon iron could absorb. 3. Graphite could be, and was, produced whilst iron was in the molten condition, possibly by precipitation. Those three points he (Mr. Adamson) had spoken of so often that it was unnecessary to refer to the details here.

With regard to melting, the authors gave in their table on p. 569 the highest temperature attained, the casting temperature, and the "time," which latter, however, was vague, as it did not state whether the "time" was (*a*) from commencing to melt the metal to casting it, or (*b*) the time the metal was kept in the molten condition before casting. When referring to time that was very important, because the difference in ratio between (*a*) and (*b*) would possibly explain why the total carbon and the graphitic carbon varied so much in the table on p. 569.

Taking the combined carbon by difference, experiments 5, 9, and 18 were closely approximate, namely 1·75 per cent., 1·86 per cent., and 1·61 per cent., and in experiment 24 the total carbon would naturally be all combined carbon because of rapid cooling by chilling, thus bringing in the question of internal stress on cooling as suggested by the authors.

The authors had unfortunately not carried their experiments far enough to take any note of crystallisation due to growth of graphite, because they had not had sufficiently high temperatures, but they had shown a physical crystallisation of iron and carbon, as against a crystallisation presumed to be due to chemical composition.

He (Mr. Adamson) was glad to know that the authors assumed the existence of grains of graphite in the molten metal, as had been shown in his cooling curves published before the Institute at the Autumn Meeting of 1911. In his opinion the authors were quite right in suggesting that those grains of graphite might serve as nuclei for the crystallisation of the graphite. He did not, however, agree with the authors' statement that the maximum temperature which molten metal had reached had apparently no effect on graphitisation.

Charpy and Grenet's work proved the contrary. On p. 573 the authors stated that it was questionable whether graphitisation could take place by more prolonged annealing at a temperature of 900° C.; with an alloy containing practically no silicon the fact of precipitation would naturally require a higher temperature. He (Mr. Adamson) further disagreed when they said that time seemed to have no effect on the completeness of graphitisation. Unfortunately the authors' "Time" was too short to enable them to come to any conclusion.

With regard to experiment No. 14, it was doubtful if the temperature of the metal had much to do with the formation of graphite on quenching, otherwise No. 11 should have shown graphite.

The subject was intensely interesting, and showed that investigations in connection with carbon and iron were now being attempted in a right direction, which was likely to throw light on the peculiar crystallisations of iron and carbon of the percentages usually found in the pig irons of commerce.

Mr. J. E. **Fletcher** (Dudley) wrote that he had the opportunity some years ago of investigating the same problem whilst attempting to carburise the face of a mild steel plate by contact with molten carbon iron of approximately eutectic composition. His experiments confirmed the view that carbon-iron alloys within the range 2·0 to 4·3 per cent. carbon, when superheated above their true melting points and slowly cooled past the eutectic freezing temperature 1130° C., were partially graphitised. A typical photomicrograph of a 3·6 per cent. carbon alloy (Swedish iron) melted at 1320° C. and cooled slowly to 1080° C. and quenched (Fig. A) (250 diameters) showed clearly the presence of a massive primary austenite crystallite or dendrite which appeared to have frozen round a large flake or crystal of graphite. Many such cases led him to conclude that the graphite was present in the liquid metal before the austenite commenced to crystallise out. Whenever the alloys were quenched from temperatures much above their true melting or fusion points, however, the massive austenite dendrites were free from graphite and showed the presence of the zigzag constituent associated with austenite which had not attained to the saturation condition (1·7 to 1·8 per cent. carbon).

It would therefore seem that the primary austenite dendrites were cemented by contact with the surrounding eutectic and became carbide-saturated if allowed to cool slowly past the eutectic freezing point.

A reference to the equilibrium diagram showed that alloys of say 3·7 to 4·0 per cent. carbon (slightly hypoeutectic) contained austenite crystals which commenced to freeze in the saturated state containing about 1·7 per cent. carbon. The curved line of the solidus change, above the point *a* in Fig 3, possibly suggested that in the case of supercooling some supersaturation of the austenite might occur, the excess carbide thereby absorbed being thrown out during slow cooling past the eutectic point B as graphite. But in such a case the graphite would be looked for at the boundaries of the austenite and not in the centres of the dendrites. In quenching above A3 he had not noticed any such phenomenon, the graphite flakes in the austenite areas being always, as far as he had seen, within the mass as shown in the authors' Fig. 4.

Was there not another explanation? It had appeared to him that the molten alloys in question might not be homogeneously hypoeutectic and might contain colonies of hypereutectic metal which might segregate towards the mass centres of the cooling metal in the mould.

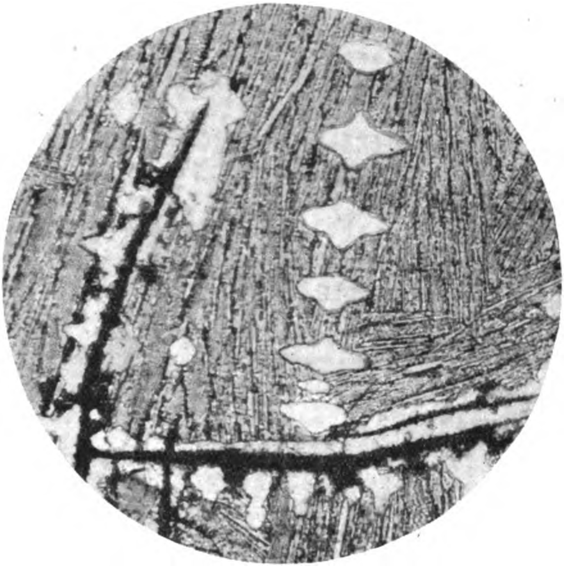

Fig. A.—Swedish Iron Melted at 1320° C., Cooled Slowly to 1080° C. and Quenched. × 250.

Such hypereutectic portions on slowly cooling past 1130° C. would deposit graphite, in fact would commence to do so at temperatures above that at which the austenite began to solidify, and hence would provide the nuclei around which the dendrites might form.

The triangular shape of mould encouraged quicker freezing at the corners and central segregation as in a cast iron ingot (see his (Mr. Fletcher's) paper on "The Cooling of Steel in Ingot and other Forms").

The general lack of homogeneity in cast irons and in carbon iron alloys within the range of the authors' experiments appeared to be bound up with the fact that, whenever the solidus line was that of the freezing of the eutectic, extreme sensitiveness to changes in temperature and constituency occurred. A mere trace of silicon might therefore be sufficient to start graphitisation in, it might be, the liquid crystal phase. It might interest the authors and others to know that the presence of manganese or chromium, even in traces, retarded graphitisation in alloys similar to those experimented upon.

THE ESTIMATION OF PHOSPHORUS IN THE PRESENCE OF TUNGSTEN.

By G. WATSON GRAY and JAMES SMITH (Liverpool).

In view of the large amount of tungsten used in the manufacture of high-speed steel, the question of the estimation of phosphorus in the presence of tungsten is an important one, but, although important, does not appear to have had the attention it deserves. Judging from numerous analyses which have come under the authors' notice, many chemists seem to find less phosphorus than is actually present. On investigating the cause of some of the low results, they were found due to faulty methods. Taking ferro-tungsten as an example, the authors found that the method adopted by many chemists was to decompose the ferro-tungsten by fusion or other methods, separate the tungstic acid by evaporating to dryness with hydrochloric acid, and estimate the phosphorus in the filtrate. This method is altogether wrong, as a large amount of the phosphorus present is precipitated with the tungstic acid as phospho-tungstic acid, and the phosphorus so precipitated is lost. Most ferro-tungstens contain only 0·015 to 0·030 per cent. phosphorus, and with these the error is perhaps not quite so glaring, but odd samples made from phosphoric tungsten ores contain up to 0·100 per cent., and sometimes even more. It is in these high phosphoric samples that the error stands out prominently. The authors have seen samples containing 0·100 per cent. phosphorus returned as containing 0·020 per cent. To illustrate this point a table of results obtained by using the faulty method described above is given, together with the figures obtained

Sample No.	1.	2.	3.	4	5.	6.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Phosphorus in filtrate . .	0·023	0·017	0·022	0·014	0·017	0·013
Phosphorus in tungstic acid residue	0·057	0·071	0·080	0·055	0·032	0·020
Total phosphorus . . .	0·080	0·088	0·102	0·069	0·049	0.033

by further examining the residue of tungstic acid for phosphorus. These results are only a few selected from a large number of samples examined.

From the above table it will be seen that the larger proportion of the phosphorus contained in ferro-tungsten is precipitated with the tungstic acid, and any method of analysis which is based on separating the tungstic acid before estimating the phosphorus must give low results for phosphorus. It occurred to the authors that there might possibly be some definite ratio between the amount of phosphorus precipitated and the amount not precipitated, but after making numerous analyses of samples of ferro-tungsten it was concluded that there was no ratio, neither have they been able to determine the conditions necessary either to precipitate all the phosphorus with the tungstic acid or to precipitate the tungstic acid free from phosphorus. These low phosphorus results not only occur with ferro-tungsten, but also with tungsten ores. To quote one example out of many, a sample of wolfram which contained 0·200 per cent. phosphorus was returned by one chemist as containing 0·030 per cent. The same state of things also obtains to some extent with tungsten steels—in fact, some tungsten steels when analysed by the usual method show only a trace or no phosphorus at all, even when it is known that phosphorus is present. Indeed, it has been suggested that the phosphorus is slagged out in making tungsten steels because the amount of phosphorus in the ingredients used was so much higher than that found in the finished steel. It appears to the authors that the discrepancy is due not to slagging out the phosphorus, but to the whole of the phosphorus in the finished steel not being obtained in the analysis owing to the cause stated above.

The method devised by the authors for the estimation of phosphorus in ferro-tungsten, tungsten powder, and tungsten ores, which has proved to be an accurate one after some years of service, is as follows:

Fuse 2 grammes of the finely powdered sample with 10 grammes nitre mixture ($Na_2CO_3 + KNO_3$ in molecular proportions) in a large covered platinum crucible, dissolve the melt in the least possible quantity of water, filter, and wash free from tungstates with boiling water containing a little ammonium nitrate (six washings are sufficient). Ignite the residue in the original crucible, transfer to a 400 cubic centimetre beaker, dissolve in hydrochloric acid, and evaporate to dryness. To the filtrate add 20 cubic centimetres hydrochloric acid, and about 2 cubic centimetres bromine (bromine, not bromine water), stir well until the liquid is distinctly coloured by bromine, add ammonia until the precipitated tungstic acid is dissolved, and then a further quantity of strong ammonia equal to one-fourth of the original bulk of the liquid. The volume of the liquid should now be about 250 cubic centimetres. Cool and add 3 cubic centimetres magnesia mixture, stir well, and allow to stand for six hours, or preferably over night. It is generally supposed that ammonium magnesium phosphate is much more soluble than it really is. The authors found that under the conditions described, the phosphorus is completely precipitated by magnesia mixture.

Filter through double papers and wash six times with ammonia water (10 per cent.). Dissolve the precipitate in hydrochloric acid, allowing the liquid to run into the beaker containing the iron, evaporate to dryness, take up with 10 cubic centimetres hydrochloric acid, dilute, saturate with sulphuretted hydrogen to remove arsenic, tin, &c.; filter, wash, boil off sulphuretted hydrogen, add 50 cubic centimetres ferric chloride (1 gramme pure iron dissolved in hydrochloric acid, oxidised with nitric acid, and made up to 1 litre), cool completely, add ammonia until a distinct dirty green precipitate is obtained, then acetic acid until the precipitated ferrous hydrate is dissolved, boil well, and filter off the basic ferric acetate which contains all the phosphorus, dissolve in hydrochloric acid, boil, add a few cubic centimetres nitric acid, and precipitate with ammonia. Boil, filter, wash, dissolve in nitric acid, and precipitate the phosphoric acid with ammonium molybdate as usual.

The method may also be used for the estimation of phosphorus in alloy steel, but as steel cannot be fused directly with nitre mixture it should be dissolved in nitric acid in a dish or wide beaker, evaporated to dryness, and baked on a hot plate until the nitrate of iron is decomposed to oxide. The resulting oxide of iron, &c., can then be easily and cleanly removed from the dish or beaker with the aid of a flexible spatula and wiping with a little damp filter paper. It is then fused with nitre mixture and the analysis proceeded with as directed for ferro-tungsten. The method is especially useful for vanadium steels, as by its means the vanadium (which interferes very considerably with the estimation of phosphorus by the molybdate method) is completely got rid of before precipitating with molybdate.

The authors have submitted the method to chemists in several large steelworks, who have found it satisfactory.

THE ANNUAL DINNER.

In celebration of the Jubilee of the foundation of the Iron and Steel Institute, the Annual Dinner took the form of a Banquet in Guildhall (by the courtesy of the Court of Common Council of the City of London) on the evening of Thursday, May 8. The President, Mr. Eugene Schneider, presided, and was supported by the Rt. Hon. the Lord Mayor of London (Alderman Sir Horace B. Marshall); His Excellency, Mr. Paul Cambon (French Ambassador); Major-General the Rt. Hon. J. E. B. Seely, C.B., C.M.G., D.S.O., M.P. (Under-Secretary of State for the Air Ministry); the Rt. Hon. Sir Auckland Geddes (Minister of Reconstruction); General C. F. Aspinall, C.M.G., D.S.O.; Sir William Beardmore, Bart. (Past-President); Sir Robert Hadfield, Bart., F.R.S. (Past-President); Dr. Arthur Cooper (Past-President); Mr. Illtyd Williams (Honorary Treasurer); Sir W. H. Ellis, G.B.E. (Vice-President); Mr. Sheriff Bannister Fletcher, F.R.I.B.A.; Colonel and Sheriff W. R. Smith, M.D., D.L.; Dr. J. E. Stead, F.R.S. (Vice-President); Mr. C. J. Bagley (Vice-President); Mr. Andrew Lamberton (Vice-President); Mr. Francis Samuelson (Vice-President); Sir Arthur Duckham, K.C.B.; Sir R. A. S. Redmayne, K.C.B.; the Very Rev. the Dean of St. Paul's; Mr. Henry O'Brien (Master of the Ironmongers Company); Mr. R. Allen Brown (Master of the Armourers and Brasiers Company); Sir Walter Harris, C.M.G. (Prime Warden of the Blacksmiths Company); Sir W. B. Peat; Mr. S. Dixon Kimber (Chief Commoner); the Presidents of many kindred Institutions, the Under-Sheriffs of the City of London, and Members and Council of the Iron and Steel Institute.

The company, which numbered 420, were received in the Corporation Art Gallery by the President and by the Lord Mayor, and on assembling for dinner in the Guildhall, grace was said by the Very Reverend Dr. Inge, Dean of St. Paul's.

The **President**, before proposing the toast of His Majesty the

King, Patron of the Iron and Steel Institute, read the following telegram from His Majesty:

> "WINDSOR CASTLE.—I am commanded to express to the President, Council, and Members of the Iron and Steel Institute assembled on the occasion of the jubilee of its foundation the sincere thanks of the King, the Patron of the Institute, for their kind message of loyal devotion, which His Majesty has received with much satisfaction. The King wishes that all possible success and prosperity may attend the work of the Institute in the next half-century of its life.—STAMFORDHAM."

The toast of "His Majesty the King (Patron of the Iron and Steel Institute)" was then duly honoured.

The President then proposed the toast of "Her Majesty Queen Mary, Queen Alexandra, His Royal Highness the Prince of Wales, and the other members of the Royal Family," and read the following message received from H.R.H. the Prince of Wales:

> "I am instructed by the Controller of the Household of H.R.H. the Prince of Wales to convey to the President and Members of the Iron and Steel Institute the following message. His Royal Highness the Prince of Wales very much regrets his inability to be present at the Banquet being held at the Guildhall to celebrate the fiftieth anniversary of the Iron and Steel Institute of Great Britain. He wishes the President and Members of the Iron and Steel Institute the greatest prosperity and success in the new era which is now unfolding itself."

The toast was duly honoured.

The President then proposed the toast of "His Excellency Monsieur Poincare (President of the French Republic) and the Rulers of other Allied States." He said that in view of the unity and close alliance which had prevailed between the Allied countries throughout the trials and difficulties of the last five years, he felt confident it would appeal to everyone present.

The toast having been duly honoured the President next proposed "The Lord Mayor and Corporation of London." He said that it was by the great kindness of the Lord Mayor and City Council that the Institute was privileged to meet in that ancient and historic Hall, the scene of many stirring episodes, political and social, through many centuries. Within those walls kings and rulers of many countries and great Ministers of State had been entertained on innumerable occasions. On rare occasions the City Corporation had granted the use of Guildhall for social festivities, such as the present one; on a previous occasion it had been granted to the Institute for the purpose of a gathering similar to the present one. They were now celebrating the attainment of the fiftieth anniversary of their foundation, and as a special privilege they were permitted to assemble here again. He thanked the Lord Mayor for his kindness and condescension, and asked all present to join him in drinking the toast of the Lord Mayor and the Corporation of the City of London.

The toast having been duly honoured,

The Right Hon. the **Lord Mayor**, in responding, said the Corporation of the City of London felt it an honour to lend its ancient Guildhall to an institution so distinguished and wielding such an influence as the Iron and Steel Institute, which represented great knowledge, great achievement, and great responsibilities. On many occasions the Corporation had shown itself ready and eager to advance the commercial well-being of London, and of the nation, which relied to a very great extent upon the intellect, the ingenuity, and the executive gifts of the men in control of iron and steel products. It welcomed in its Guildhall those whose services it esteemed so highly, and to whose continued leadership in one of the great key industries it felt it could confidently commit itself. A year ago that essential industry manifested itself in terms of guns, shells, and bayonets, of battleships and their auxiliaries, and of aircraft. The qualities characteristic of its product had been, as it were, transferred to our brave soldiers—the strength of iron and the unyielding endurance of steel. The Institute had taken a most important part in the nation's victorious warfare. The sword was now to be beaten into a ploughshare and the spear into a pruning-hook, and the resourceful energies of the industry to be used again for the requirements of the world at peace. In placing the Guildhall at the disposal of the Institute, the City Corporation was doing a national service by welcoming to the Guildhall of the City of London the Iron and Steel Institute. He was not unconscious of the importance of their visitors in matters which affected the welfare of their country and of other countries in commerce and in industry. He (the Lord Mayor) was happy in being seated between the representative of a Government on his right and the representative of a great commercial firm on his left, with whom as a nation and as Englishmen all were in perfect accord that day. They rejoiced in that fact, and they trusted that understanding might long continue to prevail.

The PRESIDENT then proposed the toast, "Peace, Progress, and Prosperity." He said:

"Your Excellency, my Lord Mayor, my Lords and Gentlemen,—I cannot allow the occasion of these toasts to pass without thanking you all for having responded to the invitation of the President and Council of the Iron and Steel Institute. I see around me those that helped to win the war and those that are building up a new world. I have certainly no intention of recalling here the tremendous efforts and the unprecedented exploits achieved during the past five years by the Allied Nations under the guidance of Ministers, statesmen, and military leaders whose names will live in history. A very long speech would fail to convey an accurate impression of what has been accomplished in their own special domains by our mechanical engineers, naval architects, civil engineers, and metallurgists, of whom you will allow me to say with some degree of professional pride that they have forged an armour proof against 'the dry powder and the sharpened sword' of our enemies, and I am quite sure that tasks of equal importance and equally efficacious have been successfully accomplished in their respective spheres of action by all the eminent corporations represented here. I would wish, however, to avail myself of the truly exceptional opportunity afforded me briefly to deal with the existing moral situation of the allied nations and more especially of the British and French nations who are bearing on their shoulders the main burden of peace.

"I believe indeed that statements of this nature, sincere and concise as possible, devoid of rhetorical flourish and made by the leaders of our great corporate Associations, may prove of use in the resettling of that new social order which the peoples of old Europe are impatiently awaiting.

"What complicates the task of men of goodwill is that many weak and short-sighted folk imagine that they possess some infallible nostrum or some general formula obtaining in every case and under every circumstance. I feel certain, however, that the great mass of French and British working-men know where their true interests lie, instinctively distrust day-dreamers and are fervently looking forward to the establishment of a satisfactory social order without revolutionary crises or civil commotion.

"Is the task an impossible one? I cannot bring myself to believe it so, and there will no doubt be found some master-builders capable of rearing the new edifice wherein every tenant can take pleasure in life provided that the social problems that preoccupy us to the exclusion of all others are dealt with by those amongst us who are worthy of the noble title of Leaders of Men, who are capable of appreciating with the necessary detachment of mind, not only the phenomena of history and economy but their own conceptions thereof, quite impersonally as matters of scientific disinterested inquiry. Such is the price we must pay to safeguard ourselves from the snares of enthusiasm or depression and the evil suggestions of precedent or routine, styled by our poet Sully-Prudhomme:

"'Cettè étrangère qui supplante en nous la raison.'

"Such is the penalty exacted from whoever desires to appraise each varying factor in the problem, according to its exact value, and the weight it bears in the domain of probabilities and possibilities.

"Let us picture to ourselves the men of our European nations as moulded during long centuries of national life and as transformed by five years of warfare. After this it may be possible for us to trace an outline of the kind of Society which affords free play for their individual activities.

"In normal times the greater majority of mankind obey the impulse of immediate self-interest. War, on the contrary, is a crisis during which man succeeds in overcoming this instinct, War thus gives rise to innumerable and extraordinary instances of self-sacrifice, and the war which we have just undergone has raised to hitherto unknown heights the spirit of patience and self-denial, a spirit more difficult to evoke and to maintain amongst soldiers than the love of fighting and risk.

"It is not with impunity that such an effort is exacted; we must expect to pay for the strain with fatigue and depression all the greater as we were at the outset less properly trained to bear it.

"The different nations visited by the war show an alarming depression of spirits, but some suffer more severely than the others. The most acute form of the malady is to be found amongst the Russian people. Straining, indeed, even before the war under the evils of bureaucratic maladministration, wasted, during the campaign, by starvation, intoxicated by the potent alcohol of anarchist propaganda, Russia has finally been, to use a simile, suddenly stricken by mental paralysis owing to the almost instantaneous disappearance of the administrative and intellectual framework of the country.

"Healthy and robust nations endowed with century-old collective minds such as England and France, have borne without irremediable internal complications the terrible consequences of the war, nevertheless they must consent to follow a definite *régime* of moral reconstruction. We are now convalescent. Of this fundamental circumstance, we must not lose sight, particularly as regards France, whose power of resilience is truly characteristic. To-day France must share with Great Britain and their Allies the fruits of a prodigious victory, the healing virtue of which will help her and them to recover. Now, doctors agree in recommending their convalescent patients to avoid excitement. Drugs are no longer prescribed and surgical operations are unseasonable. Are we and they to choose, therefore, this critical time to call in any hare-brained quack whose experiments would be dangerous, to say the least, even in the full flush of health?

"We have recently discovered how deeply and how diversely the moral consequences of the war vary according to the nations concerned; we must anticipate that they will vary equally according to the standing of the individuals. It would therefore be imprudent to draw hasty generalisations. It is necessary, on the other hand, to endeavour to forecast the motives which will influence our different classes of countrymen in this new era of peace. This is no easy task, since it involves nothing less than a complete psychological study of a people, and that of the different races that have moulded it, and whose traits have survived, with more or less admixture, through successive generations.

"Among the principal classes of population, the inquiry must be instituted, after the fashion of a geologist, exploring stratum after stratum of the subsoil. Nor should we lose sight of the profound and intimate interdependency of these classes whose perfect equipoise will prevent some fatal cleavage in the rock or slip in the sand.

"Let us take as an example, one of Kipling's well-known characters, the Captain of the *Dimbula*, who remarks in regard to the components of his new ship:

"'For a ship, ye'll obsairve, Miss Frazier, is in no sense a reegid body closed at both ends. She's a highly complex structure o' various an' conflictin' strains, wi' tissues that must give an' tak' accordin' to her personal modulus of elasteecity.'[1]

"Certain main facts must be borne in mind; they are the high roads discernible to the expert airman amidst the maze of forest, tilled soil, and pasture land.

"After all, at the present time, the average man will only live and work so long as he finds pleasure in life. Work performed from a sense of self-sacrifice, or in obedience to a metaphysical, philosophical, or religious ideal constitutes the motive of but a very small minority. We must not shut our eyes to this truth, however unpleasant it may appear to some of us, and I even believe, as I have already pointed out, that one of the consequences of the war will have been still further to reduce momentarily the small cohort of idealists. We ultimately reach, therefore, this singular conclusion: that the allied nations who have given the best they had in them to secure the triumph of a disinterested cause against the enemy, will now be compelled to put forth every effort to keep the hurricane of revolution from extinguishing for ever the flickering flame of idealism still burning on their hearths.

"What, then, is the prime factor in the joy of life? Is it to be sought solely in the satisfaction of immediate material wants? Is it to be sought, in accordance with the example of Ruskin, in the love of a fine handicraft, practised after the rites of the Livery Companies of London or of those ancient guilds which throughout long centuries satisfied the aspirations of thousands of workers in the ancient Flemish towns of Bruges,

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[1] Rudyard Kipling: *The Day's Work.*

Ypres and Ghent? Or should it be sought in some diametrically opposite direction, in the widespread diffusion of machinery and of 'Taylorism,' which would allow of the whole of the material wants of humanity being obtained at the cost of the minimum of work, thus leaving to the workers of the future longer and longer hours of daily leisure?

"I do not think it possible to furnish any single or categorical reply to these questions, owing to the diversity of human character. What does seem indispensable is that the greatest possible number shall be sure, not only of the bare necessities of life, but also of a certain surplus, which, however slight, yet allows a man to practise thrift and to feel that he is captain of his own soul.

"It is this that infuses life into all those spontaneously formed social cells, the aggregate of which constitutes the modern state. Private families, trade associations, large or small manufacturing firms, corporate bodies of every kind, thrive all the better and create altogether a more 'living' general atmosphere, in proportion as the spirit of enterprise, love of effort and pleasure of risk are afforded opportunities of manifesting themselves, that is to say, in proportion as normal human activities find more abundant outlets. The health of the social cells to which I have referred appears to me the more robust and the more exuberant in proportion as we can, according to a saying of the Emperor Napoleon, 'ouvrir la carrière au talents.' There is in us a deep-seated distrust of those who wish the State to encroach, more and more, upon the province of the individual. As Macaulay said:

"'An academy of painting, which should also be a bank, would, in all probability, exhibit very bad pictures, and discount very bad bills. A gas company which should also be an infant school society would, we apprehend, light the streets ill and teach the children ill.'[1]

"Let us give our social groups unlimited range of action, and, in the Commonwealth, entire political power, and but few of those who compose them will then fall victims to their enemies' weariness and doubt, because they will see the direct outcome of their efforts, enjoy the fruit of their work, and feel the necessity of those elements of order which differentiate a living association from the mere human herd to which Bolshevism reduces mankind. Progress should mean increasing the direct interest that each member of any one of these organisms has in the prosperity of the whole. In our great industrial enterprises the humblest of the workmen or the most insignificant of the employees should have it brought home to him in the most emphatic manner that masters and men are linked together by the strongest of ties, communities of interest. He should take to heart, as he would his personal concerns, the vicissitudes that his own establishment experiences, the success it achieves, the transformations it undergoes.

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[1] *Essays*, by Lord Macaulay, "Gladstone on Church and State," vol. ii. *Collected Essays.* 1858.

"Certainly the road ahead is a long one for those who, like ourselves, seek to attain by systematic progress this yet far distant goal. We shall for a long time to come have to expend a wealth of ingenuity and of patience to educate the broad mass of workers to the point of viewing correctly and without prejudice the relations between capital and labour, masters and men. What is involved is indeed far more a radical transformation of spirit and of thought than the framing of more or less ingenious scales of wages. It is also necessary that this transformation be accepted unconstrainedly under the impulse of common sense alone, and based simply on the facts themselves, divested of those formidable stumbling-blocks, pedantry and pseudo-science. This is a complex task, necessitating infinite delicacy of feeling and tact on the part of those to whom it is entrusted—our young civil engineers. I feel convinced for my own part that the natural sociability of our races, their innate sense of frankness and loyalty, and their capacity for enthusiasm constitute the most favourable pledges of the success of this new gospel to the workpeople of Great Britain and of France. It must not be said of us that we have failed to explain with perfect sincerity to our workpeople the true state of affairs in the industrial world of to-day, or that we have failed to remove the fallacies upon which communism is based. Thanks to this action, common sense will reassert itself, and no longer will it be sought to build up the New Social World on *a priori* statements, neither proven nor impartially investigated, which would be nothing less than a perilous perversion of that social welfare, the search for which is the obsession of all noble-minded men.

"From whatever side we approach the social question, the appeal to experience and historical common sense as well as the direct examination of the moral situation of the working-class, alike yield the same answer: we must at all costs prove by overwhelming evidence that the communistic dream leads to the systematic degradation of human energy, the general lowering of will-power and intellect, and the permanent over-lordship of heartsickness and boredom, in sum, to the gradual extinction of the vital flame. But we must also show ourselves capable of exercising the necessary directive and discriminative capacity, and that we are prepared to devote ourselves to the gigantic task. The best method to adopt is to let the facts speak for themselves, without giving up more time than is necessary to words or writings.

"The requisite—yet almost entirely lacking—relations between the mass of the working-class and the élite of the administrative class can only be secured by a somewhat similar movement in both. Our future captains of industry must have learned to know their men otherwise than many do to-day; and our workpeople must also have some means of judging their leaders other than by hearsay.

"We have all undergone technical courses in metallurgy, engineering, and electricity, which have been well adapted to teach us to manipulate material as well as to teach us the limitations of our control over it. How many of our contemporaries have learned how to deal with the human mind or are familiar with the psychology of the masses—a subject far more intricate than is generally supposed? Our military chiefs certainly owe a large measure of their success in the recent war to the fact that the study of the psychology of the soldiers in modern armies has been given a foremost place in the curricula of our military academies. The study of the mentality of the soldier had already as early as 1870 occupied the attention of Colonel Ardant du Picq. Such a military writer as Ardant du Picq should be an example to our future captains and generals of industry. To obtain the desired result there is but one way: our engineers must first of all include, in the arrangement of their studies, a few months' probation in the workshop as ordinary working-men, and they must never lose the benefit of that early contact, but in after life should continue to maintain direct and natural relations with the men.

"I fully appreciate the difficulties of the task; I am perfectly aware that student-engineers will be, at any rate at the commencement of their careers, indifferent workmen in the technical sense. I am perfectly aware likewise that it will necessitate on their part, later on, infinite tact to overcome the natural distrust of the workers and to enlist their sympathy. All these difficulties can be overcome by men of intelligence endowed with what Pascal termed 'esprit de finesse,' which is a far more useful asset for our future industrial leaders than the most elaborate scientific equipment. Moreover, the Western working-men will naturally appreciate leaders who so readily and pluckily submit to their criticisms.

"In their turn, the engineers have much to learn from the men. The latter are, for the most part, keen observers. If they are not able always to explain what they see, their empiric knowledge is often much keener than that of scientists.

"Above all, however, our young men will learn all about their ideas, even their prejudices, and it cannot be doubted that in due time by interpenetration of the two classes, a great step will be taken towards a better understanding.

"You will remember, my Lords and Gentlemen, that conception of Clerk Maxwell, of a tiny 'daemon'—some Ariel from Fairyland—suddenly appearing on our planet and sorting the molecules of oxygen and nitrogen as easily as we ourselves sort a mixture of grain in a sack.

"Now it devolves upon us alone to set free a number of Ariels at present shut up in the 'pine-rifts' of the social world, and entrust these benevolent beings with the task of sorting out the human molecules and banding them together into brotherhoods, men of good-will.

"By acting thus, we shall in truth be following up a Law of Life; I am, for my own part, convinced that nature bids us in clear language so to act. Whenever, indeed, we seek to classify the elemental phenomena of life in relation to the physical phenomena, we see that they correspond to normally irreversible transformations that a hidden 'daemon' has rendered for a time reversible.

"This mysterious power, which is life, exercises no influence upon the physical and chemical relations between the molecules that constitute the human body; it does not interfere with the mechanical law of the equivalence of work and heat; no process of analysing or weighing can therefore bring it to light. It exists, nevertheless, and its action is continuous, for the moment it disappears, the phenomena thenceforth occur in all their natural order; that is to say, in the direction of a continued increase of entropy, which means, in this instance, the prompt dissolution of the body thus abandoned by the vital spark. And I repeat, it only depends on us to create and maintain amongst mankind the power capable of infusing life into our communities, and of enabling them to evolve along the lines we deem the best. There is nothing specially mysterious in all this, inasmuch as we ourselves constitute the cells of these organisms and inasmuch as we can set free the Ariels and good fairies destined to play, amongst mankind, the part which Maxwell assigned to his 'daemons' within molecular space.

"Everything impels us to the attempt for improvement, seeing that it can be brought about by human means. The task, immense though it be, does not exceed the resources of energy and enthusiasm which the British and French peoples can pool. The ancient rivalries of a bygone day and the old distrust have disappeared for ever in the memory of our two nations; they have been dissipated in the smoke of battle; the sacrifice of our soldiers spread over four years has, as its reward, the noblest fraternity of arms that has ever been known in the annals of war. Nothing can in the future destroy this bond forged in the midst of war's alarms and agonies, and which has been able to resist the despairing assault of the enemy. In peace as in war, in the workshop as in the trench, there will reign the same faith in the righteousness of that common cause for which we have had the will to fight and to win.

"There is no more beautiful promise, during these days of trouble which are the last echoes of the great convulsion, than the blossoming of that affection between people and people which will confer upon our two nations a fresh lease of youth and must necessarily react by cementing mutual trust in all the economic or social relations between our two countries. An alliance like that between England and France is unexampled in history and in it lies our best hope for the future:

"Peace, Progress, and Prosperity."

The Right Hon. Sir AUCKLAND GEDDES, K.C.B. (Minister of Reconstruction and Acting President of the Board of Trade), in responding, said: Mr. Schneider's thoughtful and eloquent speech gave food for reflection which could be carried home and pondered over. It suggested to his mind the text: "Ye that have escaped the sword, stand not still." That seemed to him to be the motto which underlay the whole thought and structure of the speech. The definition of a State as an assemblage of groups embodied one of the newer thoughts with regard to social organisation. The stable democratic State of the future would be a group of groups of groups, a distant ideal towards which, unconsciously but none the less surely, all were now moving, precept by precept and line upon line. In that group the common interest would be the unit, and not the man thinking only of himself. At the present moment the country was full of problems which demanded instant solution. The whole life of the nation had by five years of war been disorganised and the social fabric shattered. As they sat there that night, after a sumptuous banquet, in peace and comfort, it was only by an effort of mind that they could recall that there were in Europe hundreds of millions of people faced with ruin and starvation unless the life of Europe were started once again and the streams of trade again flowed through the markets of the world. It was no time for dreaming; it was a time for action, guided by such knowledge and intelligence as God had given them. There were centres and foci of diseased mentality that were growing, and might spread, and infect vast areas of Europe. They were passing through one of the very greatest periods in the history of mankind. Only the day before at Versailles, a place haunted by the memory of Germania triumphant, Germania in defeat had received a statement of the price of atonement which must be paid before she could be readmitted to the community of nations. What a moment and what a triumph that had been! No man, he thought, had ever in the history of all the world stood in so dramatic, so moving a position as had the Prime

Minister of France, Mr. Clemenceau, on that occasion when he handed to the German delegates that document which he, through his strength, his fire, and his indomitable courage, had done so much to make possible. It was no moment for vulgar boasting; rather should they approach the event with minds imbued with a proud thankfulness for the great valour, the undying glory of men of many races, of many nations, and of many colours, who had carried to victory the cause of democracy, liberty and freedom. And as we think of that great moment in Paris, let us think also of those countries lying now destroyed and desolate in the East. Within the last few days—at the outside weeks—he (Sir Auckland) had spoken to men who had come back from Russia, from various parts of Germany, from Hungary, from Austria, and from the new States that were arising. In substance they had all said: " We have seen that dying world—people hopeless, helpless, workless, starving—simple folk who cannot understand the fate that has come upon them—men and women who approach us and say, ' Won't England, won't France, won't America, help us to get back to life, for if this goes on there is nothing—nothing—for us but to die, literally to die of starvation?' " From that great dying body in Europe came strange movements and strange cries. What was Bolshevism but the death-rattle in the throat of a civilisation? It was not a thing by which men could live; it was a sign of approaching death. Bolshevism in all its forms might very soon be manifest in countries where now it seemed unlikely to be found. Peace was indeed an urgent need for Europe, and with peace, trade, because without it what was there for all those peoples to look forward to but death? They were the children of industry; they were the children of steel, of steam, and of credit. Without those things the great teeming populations of the cities could never live. " On you in this country " (said Sir Auckland Geddes), " on your fellows in France and America, and on all merchants and manufacturers and business men in those lands, lies a great burden, for it is through you and through your fellows that physical salvation alone can be found for Europe."

Proceeding, he said it was not only in Europe that there was cause for anxiety; darker and more menacing storm clouds were gathering over Asia. The emotion of religion was as powerful to-day as ever it was to make men die gladly for the faith that is in them. Religious fervour was being stirred up in all those lands which had looked to Constantinople as the seat of the Caliph. The position was threatening; there might be wild fighting between tribe and tribe and little nation and little nation, simply for the right to live. Movements were visible everywhere; strange influences were at work; and the only things that would stay them were trade, commerce, and the hope that prosperity might once again be built up.

During the last few weeks he had had many representations made to him by manufacturers and merchants who said, "We cannot stand; we will suffer disaster unless the Government comes to our aid, unless the Government protects our trade, unless the Government prohibits imports of similar kinds of goods." There were many cases where the Government could help, and where it was doing its best now to help; but there were many cases where what was lacking was an appreciation of the importance to the whole of civilisation of getting trade going and of taking some risks—great risks, it might be—in getting it going. The Government could not bear the whole burden, and sometimes when it tried to bear a part of the burden it was assailed for introducing the dread hand of bureaucracy into the business. It was one of the most difficult problems that the mind of man had ever had to try and solve—to adjust the balance between Government help and non-interference; *laissez-faire.* There were men who came to him and said: "It pays us better to have a small turnover and keep prices high than it would do to have a large turnover and have prices low." He implored such men to remember that that way lay disaster to the whole country. If only manufacturers forming, as some of them did, rings to keep up prices would say: "No, let us get the prices down as low as we can and get this trade stream flowing," then indeed they would be doing something. The extra penny was the thing that was strangling trade now more than anything else—the little bit more of profit on each article. The whole world, the whole of civilisation would crack, the whole of the credit system would be shattered, not only the credit system of this country but of the world, beyond hope of immediate repair, unless the trade streams flowed again, and the only way to start them was to get prices as low as they could possibly be got. He had looked forward to addressing those present that evening, their great corporation, which represented the greatest, he believed, of all manufacturing industries, because he knew the harm, the absolute ruin, that that policy, which some manufacturers had adopted, was going to bring not only upon us but upon those overseas who, if the policy were different, would ultimately become our greatest markets. The policy of high prices which was in vogue was doing more now, every month, to damage the country than a further month of fighting would have done. He hoped what he had said might pass beyond that gathering, because it mattered more than anything else now that someone should say what he had said, and that the country should believe it. Higher wages, of course, had to be allowed for, but there was no reason they should seek higher profits. He would say, " Get the trade going, and the profits will come in." Wages were high because money was cheap ; it had depreciated. There were comparatively few trades that were paying in real value to the workers more than was paid in real value before. All he pleaded for was that no one should, through a desire to gain over and above a fair gain, add to the difficulties that existed. The cost of food, the cost of living, were merely expressions of the fall in the value of money, for reasons beyond the control of man.

What did the word " peace " mean ? There were few more difficult words to define. He thought " peace " meant the joyful acceptation of the reign of law, and world peace the joyful acceptation of that reign by all mankind. He begged the merchants and manufacturers of Great Britain if that were a fair meaning of the word " peace," to let it sink deep into their hearts, and to remember in their business that they had drunk to such a peace in the old Guildhall that night. Peace was subjective, not objective ; it was not a question of a signed treaty only—that was a mere first step on the way to peace. Beyond that lay the destruction of old rancours, old jealousies, old fears, more enduring than any vellum, more lasting than any brass. Those had to be destroyed, to be wiped out from the mind of man. In conclusion, he would say: " I too drink to peace, prosperity, and progress, but the peace I drink to is the universal, joyful acceptation of the reign of law."

"The Guests."

Sir **Robert Hadfield**, Bart., F.R.S. (Past-President), proposing the toast of the guests, said that in the President himself they had both a host and a guest—a guest of honour indeed. The magnificent services he had rendered the cause of the Allies at the great Le Creusot works during the war put them all under a deep debt of gratitude to him. To those who laid aside for a time the making of commercial products to produce munitions for common defence against the enemy, the world in general was greatly indebted. Who before the war would have thought it possible that, in three days and upon one front, close upon 65,000 tons of ammunition would be fired away? The Hun, however, would have it so, and the Allies had followed his lead, and eventually, in the application of science to warfare, whether in chemistry, physics, electricity, civil and mining engineering, metallurgy, or other sciences, had beaten him at his own game. The debt Great Britain owed France in metallurgy suggested the names of Martin, Brustlein, the Terre Noire scientists—Gautier, Euverte, and Pourcel—Osmond, Héroult, Le Chatelier, Guillet, Charpy, and many others. The President when war broke out was Mr. Greiner, the head of the Cockerill works, who fought and died for his country, largely owing to his ill-treatment by the enemy. It was a great pleasure to see present his son, Mr. Adolph Greiner, and he asked him to convey to his brother, Mr. Leon Greiner, and the Cockerill Company, their best wishes for its rapid and complete reconstruction. An Honorary Vice-President and a recipient of the Bessemer Gold Medal, Dr. H. M. Howe, of Columbia University, New York, was to have been another guest, but unfortunately he was not present, owing to a chill. The Institute offered him, as a Past-President of the American Institute of Mining Engineers, which has just held its 119th meeting, their heartiest congratulations on the great success of the Engineering Societies Building, New York—a movement largely initiated by that body—which was the technical home of some 60,000 technologists. Would that similar facilities existed in Great Britain, where they are indeed badly wanted. On July 27, 1906, he (Sir Robert) had the honour of presiding at the Annual Dinner in this same historic Guildhall when the late Dr. Raymond was present and made a memorable speech. He would ask Dr. Howe to take back to the Institute their sincere sympathy in the great loss it had sustained in the passing away of one who had done so much for metallurgy in the United States. Dr. Howe would also be interested in knowing that his countryman, Mr. A. F. Shore, of New York, who had done so much to help science by inventing the Shore scleroscope, had just been awarded the first Hadfield prize for the study of hardness tests by the Hardness Committee of the Institution of Mechanical Engineers. There was also present General Aspinall, who was the British general who rescued Douai and received the flag of that city. There were also present the three Presidents of the leading Societies of Technology—Sir John Aspinall, Dr. Edward Hopkinson, and Mr. C. H. Wordingham, representing respectively the civil, mechanical, and electrical engineers. The great importance of metallurgy to the world was now admitted by all. What would the world be like if we took away iron and steel? What would become of the whole fabric of our life? The world to-day was built on a foundation and framework of steel, and the metallurgist was the master of steel as well as of all those other material things which play a part in life. There was one nation at least whose citizens were not present on this occasion, although they played no small part in metallurgical progress, not so much in inventing as in applying of the work of others. Whether that people would ever again be taken into the metallurgical brotherhood would depend upon themselves. It was a happy augury that the Institute was holding its Dinner in that historic Hall on the very eve, practically, that a firm, just, and lasting peace appeared to be definitely in sight. Finally, the members would warmly greet the Lord Mayor of London, Sir Horace Marshall, to whom their heartiest thanks were due for his hospitality, and that of the Corporation by allowing the use of Guildhall on so auspicious an occasion. He (Sir Robert) offered in the name of the members present a most hearty welcome to their guests, coupled with the name of the French Ambassador, to whom they would accord an especially hearty reception, and of General Seely, who had done so much for aeronautics. It was to be regretted that he did not arrive at the Guildhall that evening by aeroplane. He (Sir Robert) hoped he would have the greatest possible success in the responsible position which he now occupied.

His Excellency the French Ambassador (M. Paul Cambon), who received an ovation on rising to reply, asked permission to speak in French. He was, he said, much impressed with the mark of sympathy which had just been shown him—a sympathy which he was very happy to transfer to his country. He had long been aware of the sympathetic ties which united Great Britain and France, and he could say that a new proof of them had been afforded when, in the full war period, at a time when both countries were fighting shoulder to shoulder in the most noble and most just of causes, Mr. Schneider had been appointed President of the Iron and Steel Institute. The intimacy that obtained between the two nations had to be "solidified" and made lasting. The war which, he hoped, would end in a few days by the consummation of a just peace, had been a manifestation of the conscience of the whole civilised world rising up against German barbarism. The two nations had fought jointly for justice, and justice had triumphed. The triumph had to be rendered durable; it had to lead to the rest which the whole world had a right to demand. It was to be hoped that, by the intimate union of Great Britain, the United States, and France, it would be possible to ensure for the whole world peace in liberty. The Lord Mayor had spoken of the services which the Iron and Steel Institute had rendered during the war; he (the speaker) would add that all the Allies had profited by those services. Those services were still required, political questions had to be set aside, and the same services were now demanded in connection with the various social considerations now confronting the nations. In social considerations public opinion came in, and bodies such as the Iron and Steel Institute were precisely those which formed public opinion. He felt sure that, as had been the case in war, so in peace time those bodies would be able to rise to every emergency.

Major-General the Right Hon. J. E. B. Seely, C.B., C.M.G., D.S.O., M.P., Under-Secretary of State for Air, who also responded, said it was a high privilege to respond for the guests at that historic banquet, representing the fiftieth year of the Institute and the year of victory. It was a glorious thing that in the peace that had been won the victory had been achieved side by side with France. Nor could they forget that great host of those who contributed to victory, but who were no longer with them. They could not forget that their President gave his son to the proud cause of liberty. They rejoiced to think that those who remained enjoyed the fruits of victory, and speaking on behalf of all the forces of the Crown he (General Seely) felt he could say that it was to iron and steel that they owed that victory. The valour of those who fought would have been as nothing if the industry had not supplied the right material. Having spent nearly four years at the war, he knew full well what it meant to have enough shells, to have enough bullets, to have enough tanks, and to have enough aeroplanes. He had known what it was not to have enough of them! The country was grateful to those of them who, by their energy and skill and by the energy and skill of the men whom they controlled, gave us the necessary power to secure to the valour of our men the victory. Sir Robert Hadfield had asked him why he (General Seely) did not arrive by air. He would impart the reason to the Lord Mayor. When he came past his City in an aeroplane in the ordinary course of his business at the House of Commons, he passed through the Tower Bridge. As he went by he saw two of His Majesty's subjects shelter their heads for a moment, and that wonderful figure of a City policeman standing up shaking his finger at him. There followed a strange thing, that he, the responsible Minister in the Air Office, had to answer the question of what was meant by an aeroplane flying over the heads of the citizens of London in too close proximity, and he had been requested to forbid it for ever! It was for that reason that he was unable to arrive at Guildhall by the most safe and the most convenient method of travel.

He wished to say to the members of the Iron and Steel Institute that the future of the air lay with them. Better and better steel was the one thing that will make air travel really safe and really efficient, and would really link together the outlying parts of the Empire and perhaps the nations of the world. Let them give

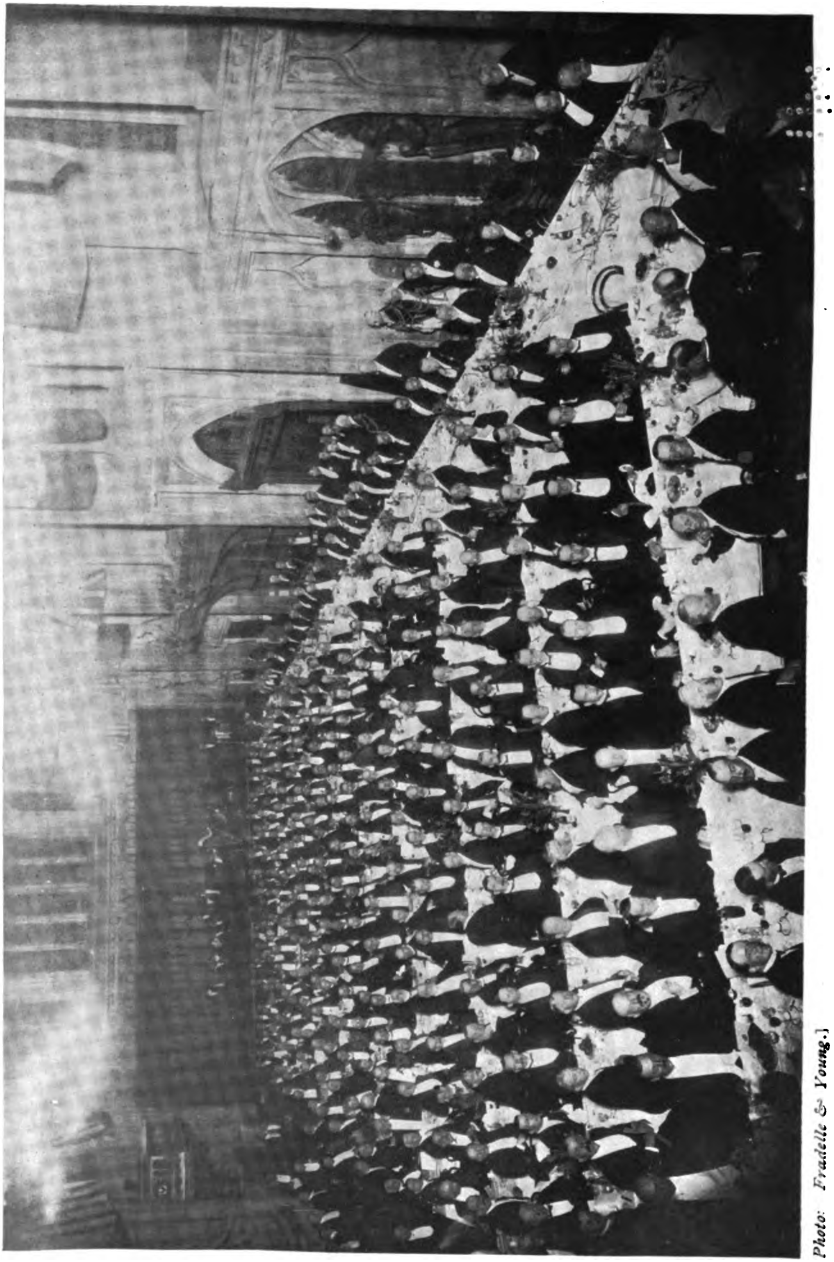

Photo: Fradelle & Young.]

IRON AND STEEL INSTITUTE JUBILEE DINNER
held at the Guildhall, London, Thursday, May 8, 1919.

To face p 608.

him an engine at 1 lb. per horse-power and they should see marvels. Let them give him one at ½ lb. per horse-power and they would see things more marvellous still. During the past five years there had been such a reduction in weight per horse-power that he felt he was not asking too much. "I am not"—he said—"asking you too much. Give me ½ lb. per horse-power and I will guarantee that we will make air travel as safe, as certain, and as profitable as any other method of travel in connection with those great developments to which Sir Auckland Geddes has referred if the world is to be saved." The members of the Iron and Steel Institute had the science and the skill at their disposal to make that entirely new field of activity a real vital force in the activities of the world. It was on iron and steel that it relied. Finally, he would say this. He rejoiced to be privileged to reply to the toast of the Guests that night. It was almost his first public appearance since the war, and his first appearance in that great Hall, although he had often spoken in it before the war. The French Ambassador, their faithful friend through twenty-one years, had responded in the hour of victory. On each side were to be seen emblems of victories that were won fighting against France. In the Arc de Triomphe were to be seen emblems of victories which France won fighting against England. In all those long years of strife he thanked God that it could be said "We fought like gentlemen." We learned to respect each other more and more; and now in the soil of France there lay countless dead, French and English, linked together in the last embrace which signalled the eternal unity of France and England. In his most eloquent speech, Sir Auckland Geddes had asked, "How shall we define peace?" It was difficult, but they could define victory. France and England knew what victory meant. They had had their victories one over the other, and now at last they knew what victory meant in common. In the new era which the Prince of Wales asked them to signalise that day, he (General Seely) thought it might be said on behalf of everyone in that Hall, that they marched forward with happy hearts, purified by the sacrifices they had gone through, knowing that they had done their best in a just cause, and determined that France and England should march forward for ever towards the light.

Sir ARTHUR DUCKHAM, K.C.B., in proposing the toast of the Iron and Steel Institute, said that, as a member of the Ministry of Munitions, he could say they had perhaps received more benefit from the efforts of those present than any other Department of the Government. He had made many friends among the members of the Iron and Steel Institute, whose assistance was beyond all price to the nation during the war. The most wonderful thing in connection with the steel production of this country was the way in which steel manufacturers changed from one kind of steel to another. The call was for very special steels for special purposes which became greater as man power decreased, such as steel for shells, aircraft, and so on. In the year 1918 there was produced nearly 1,000,000 tons of shell steel, 119,000 tons of steel for tanks, and 170,000 tons of steel for aircraft, which showed the magnitude of the task. There were also all the many new makers who came together to make this new steel, who were assisted by those who already knew how to make steel. Men like Sir Robert Hadfield and Sir William Beardmore, like their President, Mr. Schneider, gave advice and knowledge to those new makers and helped them in every possible way. The knowledge possessed by the steelmakers of the country was pooled, as it was pooled by all the contractors who helped the Ministry in the manufacture of munitions. As the months went by the task became more and more difficult, because there was a call for better classes of steel. The 1 lb. per horse-power mentioned by General Seely was very nearly accomplished at the end of the war. He (Sir Arthur) was certain that if the war had gone on for a little longer and the industry had got into its full stride—because it had not got into its full stride at the time of the Armistice—that would have been accomplished. Another most wonderful thing to him was that on the cessation of hostilities the work was abruptly stopped, yet the conditions attending that stoppage were met unflinchingly. Then there was the question of shipbuilding. Great anxiety was felt by the Cabinet and by the Prime Minister lest there should not be enough ships to go round. The shipbuilders called out for more steel—they were very short at one time, but eventually the manufacturers gave them so much steel that they were forced to cry "Enough!"

He (Sir Arthur) had heard a great deal lately about the question of nationalisation. He lived in an atmosphere of nationalisation all day and all night. The few heads of the remarks he was making were put down while Mr. Smillie was cross-examining the Duke of Northumberland at the Coal Commission. The question of nationalisation was a serious one. It was a question that had been brought forward by a large number of the citizens of Great Britain, and it could not be ignored. Sir Auckland Geddes had said he believed in group systems. The members of the Institute would have to come together in group systems and forget their old individual and insular systems of working that existed before the war. They would have to come to each other's assistance and help. It was stated in the Report of the Council that an organisation had been set up "whereby steelworks and their laboratories, the various universities or equivalent institutions, as well as commercial laboratories and analysts in various centres of the steel industry, would collaborate with the National Physical Laboratory in the preparation of standardised samples." That was a good move, but was it enough? It only dealt with the preparation of samples. Could they not interchange ideas; could they not cast their bread upon the waters, as Sir Auckland Geddes said? Something of that nature combined with a form of Whitley Council, and also with another body which he was sure certain of the workers would appreciate more than anything else, a Works Committee—he was speaking with knowledge, because he was connected with a company that ran its affairs with a Works Committee and found it of the greatest assistance and help—would constitute real progress. The Works Committee to which he referred passed resolutions, and not in 1 per cent. of the cases in which resolutions had been passed had it been necessary for the management or directors to make any movement otherwise than in accord with the men. If the members would exchange figures of costs and statistics freely and fully, it would be all to their good. In America more than in Great Britain greater freedom existed in the exposition of ideas, patents, and so on, to other people. He believed it was Renan who had said that what made a nation was the memory of the great things that its people had done together, and the will that they had to accomplish others. That was true of industry. Their industry had done great things in this war; it had, it might be said, won the war, because without it it would have been impossible to have carried on. He had to couple with that toast the name of Sir William Beardmore, who had been a very great friend to the Government, because when it had a difficult job to do it could always rely on Sir William Beardmore doing it. In addition to the routine work of peace times, which were manifold, he cheerfully tackled the building of Zeppelins and of tanks, and he built the biggest aeroplane that had ever been built. He succeeded in all his undertakings. Before the war Sir William Beardmore was in the first rank; after the great trials that had been passed through he still remained in the foremost rank. He (Sir Arthur) asked them to honour the toast of the Iron and Steel Institute, coupled with the name of Sir William Beardmore.

Sir **William Beardmore**, Bart. (Past-President), thanked Sir Arthur Duckham for his kindly references to himself. The Iron and Steel Institute was founded in 1869, just fifty years ago. Amongst those who founded it were Sir Lowthian Bell and Sir Henry Bessemer. The Duke of Devonshire was the first President, and filled that office in such a manner that he stamped the new organisation at once with a national and even cosmopolitan character. The Institute started with a membership of 100; it had now over 2000 members. In 1869 the total quantity of pig iron produced in the United Kingdom was 5,500,000 tons; in 1913 it was 10½ million tons. During the war it fell slightly, owing to conditions prevailing. The production of steel in 1869 was 215,000 tons; in 1913 it was 7,700,000 tons. To-day steel industry stood on the threshold of a new era. The country was passing through a crisis. Some people were apprehensive; others were disturbed. He, personally, was no pessimist. He was persuaded that the good sense of the British working-man would in the long run assert itself. Never in the country's industrial life had the employer been more eager to meet the just claims of the worker. It was on the working-man that almost solely the future fortune of the country depended. In the case of the steel industry that feature was most pronounced. Steel was the greatest necessity of commerce; into the cost of its manufacture labour entered very largely, whether in respect of the mining of coal and iron or in the melting of the steel. The employer was willing, by research and enterprise, to ensure that the best mechanical means would be afforded the men to produce goods at a price that would encourage foreign buyers. The present price of steel was three times higher than before the war. The problem was to bring that price down, while giving the worker better wages and a better time generally. It can be done if the men would do their part, would work loyally, with vigour and with confidence, but unless they could beat their competitors in price, the future would be uncertain. That they could do so, however, he, personally, felt certain.

The proceedings then terminated.

SECTION II.

NOTES ON THE PROGRESS OF THE HOME AND FOREIGN IRON AND STEEL INDUSTRIES.

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In the preparation of these Notes the Editor has been assisted by L. P. Sidney, Assistant Secretary, and others.

IRON ORES.

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I.—*OCCURRENCE AND COMPOSITION.*

Formation of Ore Deposits.—W. H. Goodchild (*Mining Magazine*, September 1918, vol. 19, No. 3, pp. 135–144; No. 4, pp. 188–199) discusses the principles of the segregation of ore deposits from rock magmas, introducing several new factors in addition to those already put forward by geologists.

J. D. Kendall (*Transactions of the Canadian Mining Institute*, 1918, vol. 21, pp. 293–421) deals at length with the formation of ore deposits, and discusses the classification of ore deposits and sources of ore.

Iron Ore Resources of Great Britain.—The *Summary of Progress of the Geological Survey of Great Britain* for the year 1917 contains much information relating to work done by the Survey in connection with the ore deposits of Great Britain. From investigation and information obtainable estimates of proved and probable reserves of iron ore have been made and are given in the report.

The iron ore resources are summarised under two headings: (*a*) reserves more or less developed, and (*b*) probable additional reserves. The figures are:

	(*a*) Tons.	(*b*) Tons.
Hæmatites, &c.	42,500,000	75,000,000
Mesozoic ores	1,775,052,160	2,104,886,000
Clay ironstones and blackbands	1,065,637,000	6,248,475,600

Four-fifths of the probable additional reserves in the last class are credited to South Wales and Monmouth.

Iron Ore in Canada.—E. S. Moore (*Bulletin of the Canadian Mining Institute*, February 1919) describes the iron ore deposits on the Belcher

Islands, in Hudson Bay. The result of the author's examination of these deposits show that they are too lean and silicious to be of any commercial importance.

R. C. Campbell-Johnston (*Mining Journal*, December 28, 1918, vol. 123, pp. 760–761) describes the occurrence and composition of the iron ores of British Columbia. Numerous deposits of magnetite and hæmatite occur along the coast and around the bays of Vancouver Island, and operations are about to be undertaken with a view to their development. Analyses of various samples are given, the following being a typical one:

Ferrous oxide	28·61
Ferric oxide	62·24
Silica	6·10
Alumina	0·35
Lime	1·15
Magnesia	0·44
Copper	trace
Sulphur	0·017
Phosphorus	0·016
	98·923

Iron Ore in Newfoundland.—H. A. Wilson (*Journal of the West of Scotland Iron and Steel Institute*, January 1919, vol. 26, pp. 50-65), in discussing the position of the Scottish iron and steel trade in relation to basic ore supplies, describes the important iron ore deposits of Newfoundland.

Iron Ore in Australia.—Particulars, collected from official sources, are given (*Mining Magazine*, March 1919, vol. 20, No. 3, pp. 150–156) relating to certain iron ore deposits in Western Australia, New South Wales, and Tasmania. The deposits of Western Australia fall into two main classes: (1) The ores associated with the crystalline schists and other allied rocks. (2) The superficial deposits of limonite which occupy extensive areas in many and widely separated portions of the State, and the soft porous deposits of bog ore of comparatively recent origin.

The ores of Class (1) are by far the most important, and are largely developed in the Murchison district.

The most important deposit in Tasmania is situated near the Blythe River, in the north-western part of the island. In addition there are several smaller deposits, partly within the Dial range, in the north-western part, and partly in the district of Beaconsfield and Salisbury, in the north-eastern part of the island.

The deposits at Carcoar and Cadia are regarded as the most important in New South Wales. The Carcoar ore is estimated to contain on the average about 53 per cent. iron, 10 per cent. silica, and 0·09 per cent. phosphorus.

E. C. Saint-Smith (*Queensland Government Mining Journal*, August 1918) reports on the progress of the geological and metallurgical investigations in connection with the iron ore deposits of Queensland and the means of establishing an iron and steel industry. Details are given of the deposits at Biggenden and other districts.

Iron Ore in Belgium.—K. Keilhack (*Glückauf*, June 15, 1918, vol. 54, pp. 373–377) presents a study of the iron ore deposits in Campine, in northern Belgium. The ore consists of brown hæmatite and bog iron ore, and a map shows the distribution of the ore bodies.

Iron Ore in France.—A. Bordeaux (*Bulletin de la Société de l'Industrie Minérale*, 1918, Series 5, vol. 14, pp. 49–65) gives an account of the iron ore deposits of Savoy. Some important veins occur at Allevard, of which the largest, at La Taillat, extends for over 1000 metres and outcrops. This ore contains 32 per cent. of iron and 3 to 4 per cent. of manganese and is spathic. Other deposits exist at Chartreuse, with about 37 per cent. of iron. Many of these deposits have been worked for years. Anthracite deposits are also found, and American practice has shown that anthracite can be satisfactorily used for iron smelting in the blast-furnace. The percentage of manganese present in the Savoy ores shows them suitable for the production of special steels, particularly by electric methods.

A. C. Spencer (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1485–1487) discusses the iron ore resources of France other than those of Lorraine. Early estimates placed these resources at 300,000,000 tons, but since the war further developments have taken place, and a German estimate recently rated French resources (including her colonies) at 10,000,000,000 tons, which, deducting those of French Lorraine, amounts to 7,000,000,000 tons. The new resources are mainly in Normandy and Brittany, but the estimates given above include, of course, Algeria and Tunis. Small deposits are mined over almost every part of France.

The iron ores of Alsace-Lorraine are dealt with by S. Paige (*Ibid.*, pp. 1490–1496).

The Lorraine Iron Ore Mines.—Details are given of the ownership of the iron ore mines in Lorraine, nearly the whole of the iron ore area being held by the large iron and steel works in Germany. Statistics of the production of iron ore in Lorraine and Luxemburg since the annexation in 1871 are also given (*Iron and Coal Trades Review*, November 8, 1918, vol. 97, p. 517).

Iron Ore in Germany.—P. Krusch (*Glückauf*, April 27, 1918, vol. 54, pp. 261–268) describes the iron ore deposits in the Bentheim-Ochtrup basin. The region lies west of Münster, near the Dutch frontier. The ore is a clay ironstone containing on an average:

	Per Cent.
Iron	33·42
Manganese	0·19
Lime	6·05
Magnesia	1·15
Alumina	2·40
Silica	9·35
Phosphorus	0·71
Sulphur	0·32

The resources are considerable and form an important reserve for Germany.

Iron Ore in Holland.—Some brief particulars are given (*Iron and Coal Trades Review*, April 4, 1919, vol. 98, p. 412) relating to the occurrences of iron ores in Holland. Bog ores have been found in the provinces of Groningen, Overyssel, and Gelderland, along the German frontier, generally in small isolated patches. A concession was granted in 1865 for mining a spathic iron ore in Eastern Holland, but was eventually allowed to lapse without any serious work having been undertaken. An analysis of the ore showed an average of 33·6 per cent. iron and 0·2 per cent. manganese, and 0·6 per cent. phosphorus. In Eastern Holland the deposits forming the continuation of the northern German field of Bentheim, Ochtrup, and Gronau, across the border, are little known and await exploration.

W. H. D. de Jongh (*De Ingenieur*, August 24, 1918, pp. 644–648) describes the occurrence of iron ore in east Holland. The deposit borders on and is a continuation of the Bentheim-Ochtrup ore-field on the German side of the frontier.

Iron Ore in Scandinavia.—W. Lindgren (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1475–1479) briefly reviews the iron ore resources of Sweden and Lapland. South central Sweden furnishes small amounts of exceedingly pure and valuable magnetites; the ores of central Sweden are hæmatites, and the reserves may be estimated at 122,000,000 tons. The iron ores of Lapland, on the other hand, may be estimated at 1,150,000,000 tons, mostly high in phosphorus. In Norway the Sydvaranger and the Lofoten deposits constitute the chief sources of supply, which may be put at about 218,000,000 tons.

Iron Ore in Finland.—Measures have been taken for the exploitation of the iron ore resources of Finland, and a company, the Jussarö Grufva, A.B. (the Jussarö Mining Company, Limited), has been formed to work the iron ore deposits on the island of Jussarö. The ore resources are estimated at 35 million tons, and it is expected that a survey by drilling to depth will reveal more. Another company, Finlands

Malmundersökning, A.B. (the Finland Ore Exploration Company), has also been formed. The firm of Friedrich Krupp is a large shareholder in both undertakings, but does not control the majority of the shares; the share capital of each company is 2,000,000 francs, but it can be increased at any time to 6,000,000 without alteration of the Articles of Association. (*Stahl und Eisen*, October 10, 1918, vol. 38, p. 948.)

Iron Ore in Spitzbergen.—A circular and pamphlet have been issued by the Northern Exploration Company describing the operations of the company in connection with the Spitzbergen mineral deposit. The Recherche Bay iron ore deposit as examined is said to consist of many million tons of very rich ore. The deposit is now opened up about 1100 feet above water-level, and the outcrop is clearly visible on the surface much higher than this level and for at least 200 yards below it.

Iron Ore in China.—H. Foster Bain (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1487–1490) regards the iron ore resources of China as overrated and considers that in comparison with former estimates they are only moderate, and fixes the workable deposits at about 400,000,000 tons. All the deposits belong either to the Chinese Government or to Chinese or Japanese concessionaires; not a single deposit is owned by nationals of any other country. Five types of deposit can be recognised: (1) Ancient banded deposits of hæmatite and magnetite; (2) sedimentary carbonates and hæmatites; (3) sedimentary oolites; (4) contact metamorphic ores, and (5) residual deposits. As an example of the way estimates have to be revised and reduced the case of the Fu-Kien deposits is cited. These deposits have frequently been estimated at 10,000,000 tons. More careful examination has reduced this to a maximum of 2,000,000 to 2,500,000 tons, a large amount of black porphyry having previously been confounded with iron ore. Similarly the Tayeh deposits, once estimated at 300,000,000 tons, have been re-estimated at 30 to 40 millions of tons of workable ore.

Iron Ore in Brazil.—E. C. Harder (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1471–1475) points out that the Brazilian ore-fields rank amongst the six great ore-producing regions of the world (the others being the Lake Superior district, the Lorraine ore-field, Northern Sweden, Cuba, and the Wabana ore-field of Newfoundland), and that it certainly is the greatest known undeveloped iron ore district. The hard ores carry about 69 per cent. of iron and generally less than 0·02 per cent. phosphorus; the soft ore contains 60 to 68 per cent. of iron and 0·01 to 0·07 per cent. of phosphorus, and the blanket surface deposits or Canga contain 65 per cent. of iron and 0·1 to 0·3 per cent. of phosphorus. There being no economic deposits of coal near the ores, the latter will plainly have to be exported, but doubts exist as to whether this can be done profitably.

A short summary is given of a report by F. M. de Souza Aguilar to the President of the Republic of Brazil on the composition and resources of iron ore in Brazil and the localities in which they occur (*Iron and Coal Trades Review*, October 4, 1918, vol. 97, p. 381). The report was published some years ago.

Iron Ore in Cuba.—C. M. Weld (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1479–1485) briefly describes the iron ore resources of Cuba, which with its estimated deposits of 3,000,000,000 tons holds a very important place in the world's iron ore supplies. In their dried condition these ores represent 1,000,000,000 tons of iron. Hitherto only the Mayari deposits have been worked. The high contents of alumina and chromium, so far from being a disadvantage, confer peculiar value on the steel, as shown by the duplex process carried out at Sparrows Point, Maryland, where the ores are smelted. By special heat treatment the steel develops valuable tensile and hardness properties.

Iron Ore in Mexico.—It is stated by the Department of Communications and Public Works of the Mexican Government that it is probable that the Iron Mountain at Durango will soon pass into the control of a Japanese syndicate. The iron-bearing formation rises 700 feet above the surface of the level plateau outside the city. The estimated weight of the mass ore above the surface is 600,000,000 tons, and the ore is said to contain 60 to 67 per cent. of iron. The deposit extends to an unknown depth below the surface. (*Iron Trade Review*, April 24, 1919, vol. 64, p. 1097.)

Manganese Ore in the Ukraine.—K. C. Chlebnikow (*Zeitschrift für praktische Geologie*, June 1918, pp. 89–92) gives an account of the manganese ore deposits in the Ukraine. Manganese ore occurs at Krivoi-Rog, but the principal occurrence is at Nicopol and this is fully described.

Manganese Ore in Canada.—Recent discoveries of manganese ore have been made in the Cowichan district, Vancouver Island (*Canadian Mining Journal*, September 15, 1918, vol. 39, pp. 320–321). Samples of high-grade ore have been obtained from a surface exposure measuring 100 by 20 feet, and the deposit being within easy reach of a railway the ore is immediately available. Analyses show 46·20 per cent. manganese, 26·92 silica, 0·064 phosphorus, while another assay gives 54 per cent. manganese and 18·4 silica (*Ibid.*, October 1, 1918, p. 331).

Manganese Ore in United States.—J. T. Pardee and H. M. Parks (*Engineering and Mining Journal*, November 16, 1918, vol. 106, pp.

872–873) give a brief description of the manganese deposits near Lake Creek, Oregon. The deposits are confined within an area of about 150 square miles in the central part of Jackson County. About 1500 tons of ore, containing at least 15 per cent. of manganese, is in sight. In addition it is indicated that at least four acres are probably underlain by 10 feet of ore (about 120,000 tons) containing about 10 per cent. manganese. Manganese mining is a new industry in the Lake Creek district, actual development work having been begun late in 1917. Since October of that year the Manganese Metals Company has carried out operations and has erected a concentration mill capable of treating 20 tons of crude ore in twenty-four hours. This mill has been in operation intermittently since March 1918, and has produced concentrates that contained an average of about 45 per cent. manganese, 4 tons of crude ore yielding 1 ton of concentrates.

M. Haney (*Iron Age*, June 27, 1918, vol. 101, p. 1659) describes the manganese ore deposits of Nelson County, Virginia. The mines were worked formerly but abandoned owing to competition from cheaper and better ore from India. The local ore occurs in pockets near the surface as nodules in layers of yellow and brown clay. It is mainly granular pyrolusite and the following analysis is given as typical:

	Per Cent.
Manganese dioxide	90·42
Iron sesquioxide	2·24
Alumina	1·13
Lime	1·22
Magnesia	2·28
Silica	1·12
Manganese	57·16
Iron	1·56
Phosphorus	0·188

According to T. Swann (*Paper read before the Fourth National Exposition of Chemical Industries*, September 27, 1918; *Chemical and Metallurgical Engineering*, November 1, 1918, vol. 19, pp. 672–673) the production of manganese ore in the United States, which was 2635 tons in 1914, rose to 113,734 tons in 1917, and by July 1918 the percentage of metallic manganese made from domestic ores had risen to 47·9 per cent. of the total. There are numerous deposits of manganese ore too high in silica for making ferro-manganese but available for making silico-manganese, and increased use of this alloy in steel industry should liberate a considerable tonnage of shipping required at present to import the deficiency between the home production of manganese ores and the home requirements of ferro-manganese.

The problems involved in the concentration and utilisation of domestic low-grade manganese ore in the United States are discussed by E. Newton (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 379–389). To make the country independent of foreign supplies, the leaner ores found in the States would need to be concentrated or means found to modify steel-making practice. The annual requirements are about 25,000 tons of high grade ore for dry batteries and about 750,000 tons in steel making, every ton of steel requiring approximately 14 pounds of ore, corresponding with 1·8 kilogrammes of manganese. The present trade description of manganese ore is ore containing over 35 per cent. of manganese, manganiferous iron ore containing less. Other commercial ores are manganiferous silver and lead ore, while manganiferous zinc ore yields a certain amount of residuum, containing manganese and iron and resembling manganiferous iron ore. It is used for making spiegel. The effect of the metals frequently associated with manganese in these ores and residues, as well as that of silica and phosphorus, is discussed, and the various operations entailed in concentration, to render them metallurgically available in steel-making, enumerated, and the various commercial considerations to be borne in mind are briefly detailed.

Crystallography of Manganese Ores.—T. L. Watson and E. T. Wherry (*Journal of Washington Academy of Sciences*, October 4, 1918, vol. 8, No. 16, pp. 550–560) describe the character of the manganese ores mined near Woodstock, Virginia. Most of the ore examined was crystalline pyrolusite developed largely by replacement of quartz from circulating ground waters, but partly also as a breccia-filling or cement and partly as crusts coating joint surfaces in the rocks. The crystallography of the manganese oxide minerals, pyrolusite and manganite, is especially studied.

Manganiferous Iron Ore in United States.—E. Newton (*Minnesota School of Mines Experiment Station*, 1918, Bulletin No. 5) has made a close study of the manganiferous iron ores of the Cuyuna range, Minnesota, and discusses the possibility of using them for making ferro-manganese.

Manganese Ore in Cuba.—Manganese ore occurs in several provinces in Cuba, but it is found in paying quantity only near Santiago in the province of Oriente (*Iron Trade Review*, November 28, 1918, vol. 63, p. 1239). The reserves are estimated at about 700,000 tons. The average composition of the ore is:

	Per Cent.
Manganese	38·88
Silica	12·13
Phosphorus	0·08
Moisture	11·20

Chromite in the Shetlands.—A. Russell (*Paper read before the Mineralogical Society*, November 5, 1918) describes the chromite deposits in the Island of Unst, Shetlands. The mass of serpentine which runs through the island from north to south contains chromite uniformly distributed but varying greatly in character, being at times massive, but generally granular. More than thirty quarries are known, but only six have been worked to any extent.

Chromite in Cuba.—All the deposits of chrome ore in Cuba that have attracted attention are within twenty-five miles of the north coast. There are about twelve groups of deposits, all contained in serpentinised basic rocks, and they range from 1 to 50 feet in depth, with a maximum length of 200 feet. Analyses of the ore show a maximum of 43 per cent. chromium in some small deposits in the province of Havana. The largest deposits are those of the Cayoguan group, averaging 38 to 40 per cent. chromium. The most accessible are the deposits near Camaguey, but the ore is of a lower grade with from 33·7 to 36·3 per cent. chromium. (*Iron Trade Review*, November 28, 1918, vol. 63, pp. 1238–1239.)

Chrome Sands on the Pacific Coast.—J. F. Grugan (*Chemical and Metallurgical Engineering*, January 15, 1919, vol. 20, pp. 79–81) points out that interest in the chrome sands of the Pacific Coast is reviving, and that if prospective undertakings can steer clear of the undesirable associations hitherto coupled with schemes for black sands mining useful metallurgical developments may be expected to take place. The "Lagoon Sands," not far from Oregon, contain 45 per cent. of chromite and would lend themselves to concentration purposes. The estimated tonnage of the "Lagoon Sands" is 25,000 tons, and besides the chromite, the garnet, magnetite, and zircon contents possess considerable economic value.

Chromite and Nickel in the Island of Celebes.—It is reported that deposits of chromite have been found on the north of Malili on Lake Matana in the Island of Celebes. The presence of nickel ores was also reported east of Melili Kampong and elsewhere. The question of mining and exporting the ores is being studied by experts of the Dutch Colonial Government. (*Iron and Coal Trades Review*, October 18, 1918, vol. 97, p. 454.)

Nickel Ore.—T. G. Trevor (*South African Journal of Industries*, November 1918; *Mining Magazine*, February 1919, vol. 20, No. 2, pp. 120–123) describes the nickel deposits in South Africa.

Molybdenum.—S. J. Johnstone (*Journal of Society of Chemical Industry*, December 16, 1918, vol. 37, No. 23, pp. 448–450 R.) enumerates the occurrences of molybdenite within the British Empire, giving statistics of production from 1913 to 1917. The largest producing country is Canada, from whence 121 tons of MoS_2 were obtained in 1917. Queensland and New South Wales have hitherto been the most important producers in the world.

The progress of molybdenite mining in Quebec, which is the great rival producer to Queensland, the output of which it has now exceeded, is noted (*Chemical and Metallurgical Engineering*, November 1, 1918, vol. 19, pp. 654–655). It is, however, in Colorado that the biggest outputs are now being made, extensive deposits being mined at Climax, Summit County. The market is, however, a very uncertain one and exports have fallen, which suggests that the use of molybdenum in steel alloys is being discontinued, or that supplies are available from elsewhere. Various reasons for this are given, one being that ignorance as to correct heat treatment is responsible for the reduced consumption of the metal.

Genesis of Tungsten Ores.—R. H. Rastall (*Geological Magazine; Mining Journal,* September 28, October 5, 1918, vol. 122, pp. 564–565, 581–582, &c.) summarises the knowledge of the genesis, mode of occurrence, and mineral associations of the tungsten ores. Tungsten deposits may be classed under four headings: (*a*) Primary wolframite ores with cassiterite; (*b*) primary wolframite ores without cassiterite; (*c*) primary scheelite ores; (*d*) secondary (detrital) tungsten deposits. Certain minerals almost always occur in association with wolframite and cassiterite, the most characteristic among the sulphides being arsenopyrite and molybdenite. In certain localities notable amounts of the rarer elements are associated with tungsten, such as uranium in Cornwall, tantalum and niobium in Burma and at Etta Knob, and bismuth in Queensland.

Tungsten Ore in Burma.—J. M. Campbell (*Mining Magazine,* February 1919, vol. 20, No. 2, pp. 76–89) discusses at length the origin of the wolfram deposits of Tavoy, in Lower Burma.

II.—*PREPARATION OF IRON ORE.*

Calcining Kilns.—An illustrated description is given (*Iron and Coal Trades Review,* April 11, 1919, vol. 98, pp. 435–436) of the calcining plant at the Irthlingborough mines of the Ebbw Vale Steel, Iron, and Coal Co. There are sixteen kilns of the Gjers type, 30 feet in height and 23 feet diameter inside brickwork.

REFRACTORY MATERIALS.

Graphite in Australia.—T. Blatchford (*Western Australia Geological Survey*, 1917, Bulletin No. 761) describes the graphite deposits at Munglinup, Eucla Division, Western Australia.

Sands for Refractory Purposes.—P. G. H. Boswell has drawn up for the Ministry of Munitions a memoir on "British Resources of Refractory Sands" (London, 1918, Taylor & Francis).

Constituents of Fireclays.—R. E. Somers (*Journal of Washington Academy of Sciences*, March 4, 1919, vol. 9, pp. 113–126) reports the results of a microscopic examination of clays, made to determine the minerals contained in them. Thin sections of some burned samples were studied to obtain some idea of the changes that take place in burning. The examination of a large number of clays from various localities showed the presence of kaolinite and hydromines in comparative abundance. Practically every clay examined contained rutile in some amount. Tourmaline is of frequent occurrence. Epidote is occasionally seen, and zircon and titanite are common though not in any abundance.

J. A. Howe (*Transactions of the Ceramic Society*, Session 1918-19, vol. 18, Part I., pp. 27–42) furnishes some notes on the silica rocks, fireclays, and dolomite in South Wales.

Sources and Properties of Zirconia.—M. A. Granger (*Moniteur Scientifique*, 1919, No. 925, p. 5; *Chemical News*, March 7, 1919, vol. 118, pp. 115–118) describes the nature, sources, and use of zirconia, and gives a table showing the analysis of zircon silicates from Ceylon, Colorado, Norway, Greenland, and Brazil. The deposits of the latter country are of great importance, but difficult of access. Mineral containing 80 per cent. of zirconia is at present valued at £30 per ton. Zirconia when pure is one of the most refractory substances known, with a melting-point of about 3000° C. Its thermal conductivity and coefficient of distillation are also very low; it can therefore withstand sudden changes of temperature. It is chemically very inert and resists many chemical reagents. By extracting it from its minerals vessels of great chemical value such as crucibles can be made. Methods for doing this are described. In the electric furnace zirconia is transformed into carbide. As a binding material starch mixed with gelatinous hydrate gives good results. Besides its value as a refractory, zirconia is of use as an opacifier in glass and enamels, and as an abrasive.

H. C. Meyer (*Transactions of the Ceramic Society*, Session 1918–19, vol. 18, Part I., pp. 264–275) discusses the occurrence and characteristics of zirconia and its applications as a refractory material.

Properties and Composition of Magnesite.—T. Crook (*Transactions of the Ceramic Society*, Session 1918-19, vol. 18, Part I., pp. 67–147) outlines the history of the application of magnesite, its uses and occurrence. From the economic standpoint, perhaps the best way to classify magnesites is on the basis of texture and composition as follows:

1. Spathic breunnerite.
2. Spathic magnesite.
3. Compact magnesite.
4. Hydromagnesite.

The following generalised analyses illustrate the chemical differences among these various types of dressed raw magnesite:

	Spathic Breunnerite. Austria.	Spathic Magnesite. Quebec, Norway, and Washington.	Compact Magnesite. Greece, India, and California.	Hydro-Magnesite. Atlin, British Columbia.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Magnesia	38 to 44	38–47	47	42
Lime	1 to 3	0 to 10	0 to 2	0 to 2
Ferrous oxide Alumina	2 to 7	2	1	1
Silica	1 to 5	1 to 3	1 to 3	1
Carbon dioxide	50	49 to 51	50	36
Water	...	...	...	19

W. Donald (*Transactions of the Ceramic Society*, Session 1917-18, vol. 17, Part II., pp. 486–561) deals with the sources and uses of magnesites for the manufacture of refractory bricks, and the structure, physical properties, and general requirements of such bricks.

Carborundum.—S. C. Linbarger (*Chemical and Metallurgical Engineering*, September 27, 1918, vol. 19, pp. 489–491) deals with the silicon carbide refractories in common use. The latest developments have been in the direction of securing greater thermal conductivity, efficiency, and strength. The peculiar and valuable properties of crystallised silicon carbide are exemplified by the two leading varieties, "Refrax" and "Silfrax," in which the crystallisation of the aggregate is large and small respectively. Another variety, "Carbofrax," used in ceramic industries, is made by bonding graded crystal grains with special refractory clay. The mode of manufacturing the different grades is described.

Corundum.—P. A. Wagner (*South African Journal of Industries; Mining Magazine*, September 1918, vol. 19, No. 3, pp. 162–164) describes the occurrence of corundum in South Africa.

Standardisation of Refractory Materials.—Part II. of the provisional specification of tests for refractory materials has now been published by the Committee of the Refractory Materials Section of the Ceramic Society (Meeting at Swansea, October 1918). For Part I. and reference to the Committee, see *Journal of the Iron and Steel Institute*, 1918, No. II. p. 89. The present part deals with the grading of clays according to grain size. (*Transactions of the Ceramic Society*, Session 1918–19, vol. 18, Part I., pp. 251-263.)

A. Malinovszky (*Chemical and Metallurgical Engineering*, December 1, 1918, vol. 19, pp. 768–769) makes some general observations on the subject of refractory products and the conditions with which they are expected to comply, in practice.

Manufacture of Firebricks from Non-plastic Material.—G. W. Mottram (*Transactions of the Ceramic Society*, Session 1918-19, vol. 18, Part I., pp. 148-153) discusses a new principle in the method of preparing materials before moulding which applies equally to silica, magnesite, chamotte, and all classes of refractory bricks made from non-plastic bases. It may be assumed that the average percentage of calcined fireclay or grog used in making firebricks is 15 per cent. Satisfactory results were obtained with 90 per cent. grog and 10 per cent. fireclay, when the raw clay was ground to a fine slip with two or three times its weight of grog and the resulting mixture afterwards mixed with the remainder of the ground grog. The method is specially applicable to the preparation of material for silica bricks. By grinding 15 to 30 per cent. of the material with lime, clay, or other binder to a fine slip and adding this mixture to the remainder of the graded silica material, there is the necessary fine material to fill in the voids and the binder is brought into intimate contact with every particle of the silica.

Manufacture of Refractory Materials in France.—The stimulus which the manufacture of refractories has undergone in France consequent on the war, and the new processes and methods which have been introduced in that country in order to cope with the serious shortage, are described and illustrated by J. Bied (*Chemie et Industrie*, 1918, vol. 1, pp. 579–601). He deals with the raw materials, dolomite, lime, magnesia, and silica sand, and gives analyses of these, contrasting them with supplies previously obtained from Greece, Styria, and Italy. He also gives an account of the composition and modes of treating the home supplies, including refractory clays and silica, bauxite and chrome refractories. The strength of these materials and the nature of the tests with which they should be capable of complying are also discussed.

Manufacture and Testing of Silica Bricks.—H. Le Chatelier and B. Bogitch (*Revue de Métallurgie, Mémoires*, November-December 1918, vol. 15, pp. 511–531) deal with the methods and appliances employed in the testing of silica bricks. So far as chemical analysis is concerned fusion methods with sodium or calcium carbonate are not suitable and the sulphuric and hydrofluoric acid process can alone be depended on. The powdered sample must not be sifted and final grinding should be accomplished in an agate mortar. Evaporation is best conducted over an Argand burner, which can be more easily regulated than any other mode of heating.

The density of a good silica brick should not vary more than from 2·3 to 2·4. For its estimation a displacement method using carbon tetrachloride, benzene, or petrol is used. The readings are made by means of a magnifying-glass carrying a vernier ruling. A good brick requires likewise to be well and strongly made and hard at ordinary temperatures. The ordinary crushing tests are beyond the scope of laboratory appliances, and moreover the preparation of test cubes is a laborious process. Brinell tests can be used instead. If the brick be so tender and brittle as to break under the ball test it is evidence that it is useless in practice. A hand-screw press can be employed giving about 500 kilogrammes pressure, or a modified Guillery machine. The ball impressions may be rendered more distinct and striking by the interposition of a sheet of thin foil between the brick and the ball. The modes of taking dilatation and crushing tests are described.

A translation has appeared (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1435–1462) of the article by H. Le Chatelier and B. Bogitch (*Bulletin de la Société de l'Industrie Minérale*, 1917, series 5, vol. 12, pp. 49–72) dealing with the manufacture of silica brick.

The theory and practice of silica brick manufactures are discussed at length by A. Bigot (*Chimie et Industrie*, December 1918, vol. 1, pp. 712–726). The nature, composition, and properties of the raw material are described, the contributions to industry derived from micrographic investigations and the study of physical properties, and modern methods of manufacture and testing, being dealt with in detail.

A. Bigot (*Transactions of the Ceramic Society*, Session 1918-19, vol. 18, Part I., pp. 165-181) presents a study of silica products directed to determine their physical properties. The author describes the practice followed by him in the grinding of the rocks, and the burning of the bricks. From certain experiments it can be inferred that in the arches of open-hearth furnaces two new materials are formed: a brown product and a grey product, of which the crushing resistance, specially of the grey part, increases in such a degree as to improve the strength of the original product. The results of his experiments demonstrate two facts, contrary to the generally accepted opinions, namely: (1) That the grey parts of the bricks, which contain only 85 per cent. of silica and 15 per cent. of foreign matter, are as refractory as products with 95 per cent. of silica, and that, thanks to their low porosity, they are far superior as regards crushing resistance at all temperatures. (2) Though it is admitted that an excess of lime and iron oxide is detrimental, and that together they should not exceed 3 to 4 per cent. of the product, the proportion of these two constituents in the grey part of the bricks varies from 10 to 14 per cent. A short description of V. Bodin's method of testing the crushing resistance of refractory materials is appended.

The manufacture of silica brick in France from French quartzites in the Loire and elsewhere is dealt with by L. Dauphin (*Bulletin de la Société de L'Industrie Minérale*, 1918, series 5, vol. 13, pp. 137–190).

Philipon (*Revue de Métallurgie, Mémoires*, November-December 1918, vol. 15, pp. 487–509) describes the progress of silica brick manufacture in France, which resulted from the crisis in refractory material supplies in that country in 1915. Before that date little silica brick was made in France, supplies being mainly obtained from Germany. The German makers claimed that only very special grades of quartz, treated by equally special methods, could be employed for making really satisfactory silica bricks, whereas tests carried out, during the emergency, at the Dunes works of the Société des Acieries de Firminy soon showed that many kinds of quartz could be used for the purpose, and that the manufacture of bricks which could, for the most part, be advantageously used in refractory furnaces, was a matter which presented very little real difficulty. The materials employed in the preliminary experiments included lumpy white quartz from the centre of France, quartz from Normandy, sandstone from the Pas de Calais, and amorphous silica from the department of Allier. The silica in these materials ranged from 97·2 to 97·6 per cent., and the alumina varied from 0·78 to 2·40 per cent. Having formulated the requirements in a good silica brick experiments were then undertaken to see how far these materials could be relied upon to produce them. These comprised investigations on the influence of the size of the grains on the strength of the bricks and on their dilatation during drying and firing, as well as that of the amount of moisture present on that property. The effect of the presence of lime on the strength of the bricks and the nature of the hardening during heating were also studied. It was found that 70 per cent. of coarse-grained material with 30 per cent. of impalpable fines made the best mixture, the lime added being 0·6 per cent. After moulding and drying the bricks were fired for 48 hours and cooled off during 40 hours. The temperature of firing was 1300°, which corresponds with the production of good solid bricks with a very small coal consumption.

Bied (*Comptes Rendus*, May 13, 1918, vol. 166, pp. 776–778) describes experiments in the use of iron pyrites and lime as binders for silica bricks. It was found that the melting point of silica was not sensibly lowered by the iron oxide in the presence of lime. A mixture of ninety-one parts of quartz sand, nine of roasted pyrites, and four of lime, after heating for one hour at 1500° C., showed a dilatation of 3·8 per cent. Another mixture in which the lime was replaced by sodium silicate began to vitrify at the same temperature. A mixture of one hundred parts of quartz, three of pyrites, and three of lime fused at 1725°, and one of one hundred parts of quartz and two of lime without pyrites fused at 1730°.

R. J. Montgomery (*Iron Trade Review*, October 31, 1918, vol. 63, pp. 1014–1016) describes the manufacture and testing of silica brick. The refractoriness depends largely on the ratio between alumina and silica. Results are given of crushing, porosity, shrinkage, and expansion tests.

C. S. Graham (*Foundry Trade Journal*, January 1919, vol. 21, pp. 42–44) has made an examination of a silica brick taken from the transverse centre of a 45-ton open-hearth furnace after 135 charges. After fracturing the brick at right angles to the exposed face, four distinct zones were distinguished. The colour of the zone exposed directly to the furnace temperature was grey, being followed by a black, a yellow, and a red zone. The grey and black zones were divided by a distinct line of demarcation, whilst the transition of black to yellow was a very gradual one. From yellow to red there again was a sudden change. After removing the skin, the different zones were prepared for chemical analysis and specific gravity determinations. Thin transparent sections were prepared by the usual petrological methods for detailed examination under the microscope. The chemical analysis, specific gravity, and porosity of an unused brick from the same batch and of the four different zones are as follows :

	Unused Brick.	Zone 1. Depth, ⅛″. Colour : Red.	Zone 2. Depth, ¾″. Colour : Yellow.	Zone 3. Depth, 3¼″. Colour : Black.	Zone 4. Depth, 1¾″. Colour : Grey.
Chemical analysis :					
Silica	95·0	93·7	91·4	85·5	88·6
Alumina	1·1	1·1	1·8	1·5	1·0
Total iron expressed as :					
Ferric oxide . . .	1·0	1·14	1·52	5·94	5·52
Manganese oxide . .	trace	trace	trace	0·27	0·37
Lime	2·5	3·19	4·10	6·06	4·04
Specific gravity :					
Bulk	1·65	1·78	1·80	2·14	2·14
True	2·37	2·41	2·41	2·44	2·42
Porosity (per cent.) . .	30·4	26·1	25·3	12·3	11·6

All the zones show an increase in the ferric oxide and lime contents and the porosity falls regularly. The black zone, which is the deepest, has the lowest silica content, and is highest in ferric oxide and lime, due to the interpenetration of impurities, but proved to be harder and more refractory than any of the other zones.

Basic Refractories in Open-Hearth Practice.—J. S. McDowell and R. M. Howe (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 291–309) deal with the preparation and uses of basic refractories in the open-hearth furnace. Comparing low- and high-lime magnesite they find that low-lime magnesite has less tendency to slake, higher refractoriness and greater resistance to attack by firebrick, silica brick and corrosive Fe_3P–Fe_2O_3 mixture, than high-lime magnesite. Of dolomitic materials those highest in impurities and lowest in lime were most resistant to slaking, while magnesites are more resistant than dolomites both to slaking and to corrosive action. The refractory values are ranged in the following order: A, low-lime magnesite; B, high-lime magnesite; C, treated dolomite; D, calcined dolomite high in impurities; E, another treated dolomite, whose properties were investigated, and sixthly, F, a pure calcined dolomite low in impurities.

Corrosive Action of Flue-Dust on Firebricks.—J. W. Mellor and W. Emery (*Transactions of the Ceramic Society*, Session 1918-19, vol. 18, Part I., pp. 230-250; *Iron and Coal Trades Review*, October 25, 1918, vol. 97, p. 460) communicate the results of an investigation on the corrosive action of flue-dust on firebricks. An experimental furnace was used in which bricks could be exposed to the action of flue-dust at high temperature under conditions where the time of heating, the nature of the dust and its speed, and the atmosphere—oxidising or reducing—were under control. It was attempted to treat the bricks so severely as to obtain results in a few hours which would require months to obtain in industrial furnaces. The types of dust used were boiler flue-dusts, deep red-coloured dust from the top of the retort bench of a gasworks, dust from the slag chamber between a steel-melting furnace and regenerator, dust from a blast-furnace stove, red hæmatite ore, tap cinder, lime, and some others. Analyses of most of the dusts are given. Two kinds of typical fireclay bricks and three kinds of silica brick were tested. In general the penetration by the dust is greater in fireclay than in silica brick. In most cases the bond is first attacked and the coarser grains last. In silica bricks the depth of penetration by the dust is generally less the finer the grain. In the fine-grained brick the coarser grains and the bond are both attacked, while in the coarse-grained brick the bond alone is attacked. It follows that the bond offers the feeblest resistance to a corrosive slag. Under oxidising conditions iron oxide does not greatly corrode silica bricks, but under reducing conditions ferrous silicate forms and acts as a corrosive flux. The dusts apparently exert an influence on the conversion of the quartz into the low specific gravity forms even where the coarse grains have apparently not been penetrated.

Influence of Slag Temperature on Refractories.—R. M. Howe (*Blast-Furnace and Steel Plant*, December 1918, vol. 6, pp. 484–485) has carried out experiments to determine the action of various slags at different temperatures on several standard brands of firebrick. Among others, blast-furnace slag, basic open-hearth and acid open-hearth slags were used. The test bricks, each having two cavities 2½ inches diameter by ½ inch depth, were heated slowly to the temperature at which the test was to be made. This temperature was held for one and a half hours. Thirty-five grammes of slag were then introduced and allowed to react at the temperature for two hours. The bricks were then allowed to cool and were cut through the centre of the cavities. The total cross-section of the slag-saturated area was first measured by means of a planimeter. The area of the original cavity was subtracted from this, the difference representing the area of the section penetrated by the slag. This area, when divided by the linear surface of contact, gave a value representing the square inches of slag penetration per inch of contact :

Penetration of 35 grammes of slag in 2 hrs. = 0·64
" 35 " " " 4 " = 0·68
" 35 " " " 6 " = 0·64
" 105 " " " 2 " = 0·76
" 105 " " " 4 " = 0·72

Varying the brick, the slag, and the temperature one at a time the following average results were secured.

Penetrating power of blast-furnace slag (melting point 1220° C.) in square inches per inch of contact :

Brick.	Temperature of Test.		
	1250° C.	1350° C.	1450° C.
Type A	0·03	0·08	0·14
Type B	0·00	0·11	0·17
Type C	0·07	0·12	0·17

Penetration of open-hearth slags in square inches per inch of contact :

Brick.	Basic O. H. Slag. Melting-point, 1275°. Temperature of Test.		Acid O. H. Slag. Melting-point, 1450°. Temperature of Test.
	1350° C.	1450° C.	1450° C.
Type A	0·58	0·73	0·24
Type B	0·29	0·33	0·33
Type C	0·44	0·55	0·57

In each case the slag penetrated more deeply into the brick at higher temperatures. In several cases an increase of 100° C., or less than 10 per cent., resulted in nearly doubling the penetration. The increased penetration affects the strength of the brick more rapidly, decreases the refractoriness of the brick more quickly, and accelerates the chemical action of the charge on the lining.

FUEL.

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I.—*CALORIFIC VALUE.*

Pyrometry.—Temperature standards and the means for checking pyrometers are discussed in a general article (*Proceedings of the Steel Treating Research Society*, 1919, vol. 2, No. 1, pp. 30–37). Sources of error in thermocouple pyrometers, methods of checking thermocouples, their arrangement in the furnace, method of connecting to the potentiometer and correction of the electromotive force by reference to a standard cold junction temperature are briefly dealt with.

R. B. Lincoln (*Proceedings of the Steel Treating Research Society*, 1918, vol. 1, No. 6, pp. 18–24) gives a note on construction and use of thermo-electric pyrometers.

A. Mahlke (*Stahl und Eisen*, November 7, 1918, vol. 38, pp. 1033–1038, 1057–1062, 1080–1086) gives a general review of the present position of pyrometry and the principles of construction and working of modern pyrometers.

Fusing Temperature of Ash.—A. C. Fieldner, A. E. Hall, and A. L. Feild (*U.S. Bureau of Mines*, 1918, Bulletin No. 129) have made experiments to determine the fusibility of coal ash and the softening temperature with the object of devising standard methods for obtaining comparable results at different laboratories. As a safeguard against clinker troubles it is proposed to draw up specifications for the purchase of coal, to include the softening temperature of the ash, and it is necessary in the first place to devise a method which gives consistent results. As a result of the study a practical method of determining fusibility has been devised.

W. A. Selvig (*Chemical and Metallurgical Engineering*, December 15, 1918, vol. 19, pp. 826–828) deals with methods for ascertaining the fusibility of coal ash, with special reference to the coals of Western Virginia but generally applicable whenever it may, for economic reasons, be advisable to determine beforehand the clinkering and other qualities of coal ashes. The preparation of the cones used in making comparative tests and the apparatus employed are described, and a table given showing the lowest and highest softening temperatures for a number of coals.

Use of Pulverised Coal.—L. C. Harvey has published the result of his investigation of the developments in the use of pulverised coal in America (*Department of Scientific and Industrial Research: Fuel Research Board*, 1919. Special Report, No. 1).

L. C. Harvey (*Iron and Coal Trades Review*, March 21, 1919, vol. 98, p. 357) discusses the use of pulverised fuel in puddling furnaces.

H. R. Collins (*Bulletin of the American Institute of Mining Engineers*, April 1918, pp. 955-961) describes the process of pulverising coal for use in furnaces and enumerates the advantages of its application. Fuels low in volatile constituents and high in carbon require a special arrangement for their use in pulverised form, as it is difficult to support combustion unless a temperature above 900° to 1000° F. is maintained. The saving of cost in working open-hearth furnaces with pulverised coal instead of producer-gas is put at 30 to 40 per cent.

W. G. Wilcox (*American Drop Forger*, December 1918, vol. 4, pp. 492–494) gives notes on the burning of pulverised coal and the method of projecting it into the furnace.

W. G. Wilcox (*Chemical and Metallurgical Engineering*, July 1, 1918, vol. 19, pp. 35–40) deals with the possibilities of powdered coal with special reference to American practice, and discusses the economy resulting from the use of pulverised fuel and the other advantages which may accrue to industry in general and metallurgy in particular by its adoption.

The Buell-Santmyer system of using pulverised lignite for steam-raising purposes is described and illustrated (*Mining and Scientific Press*, February 15, 1919).

Colloidal Fuel.—The Submarine Defence Association, New York, has published (*Iron and Coal Trades Review*, April 18, 1919, vol. 98, p. 475) particulars of the new colloidal fuels developed under its auspices. In making an oil and coal mixture an insuperable difficulty heretofore has been the persistent settling out of the heavy coal and tar particles. At the present time, however, it is possible to suspend for months in oil 30 per cent. to 40 per cent. of coal, pulverised so that about 95 per cent. passes through a 200-mesh screen, assisting the suspension with a special fixer; and it is now possible to combine in a stable liquid fuel about 45 per cent. oil, 20 per cent. tar, and 35 per cent. pulverised coal, thereby replacing over one half of the oil.

Combustion of Lignite.—H. Kreisinger, C. E. Augustine, and W. C. Harpster (*United States Bureau of Mines*, 1919, Technical Paper

207) give the results of combustion experiments with North Dakota lignite. Two forms of lignite were used—natural lignite as mined and the carbonised residue from gas retorts. The tests were made by burning the fuels at various rates in experimental furnaces and by studying the processes of combustion. The experiments indicate that the lignite and its carbonised residue might be burned successfully on an inclined step grate with an arch extending from the bridgewall over almost the entire length of the grate. The arch turns the flames and the hot gases back over the incoming fuel, thus aiding ignition. It also directs air admitted at the bridgewall against the fuel bed and increases the rate of combustion.

Utilisation of Waste Heat.—An illustrated description is published (*Iron and Coal Trades Review*, November 22, 1918, vol. 97, p. 580) of the Brett system of raising steam by utilising the waste heat from coal and oil-fired furnaces. Sufficient steam is maintained, by using the waste heat of two coal-fired furnaces for heating steel billets, to work a battery of nine drop-hammers. The application of the boilers does not necessitate the consumption of any extra fuel in the furnaces.

Fuel Economy.—O. Duperron (*Génie Civil*, November 16, 23, 1918, vol. 73, pp. 387–389, 404–407) outlines a general scheme for economising as far as possible the consumption of fuel in iron and steel works by the introduction of the use of pulverised coal, the extension of the use of compressed air, the installation of recuperative reheating furnaces, and by the extended use of waste gases and producer-gas.

J. B. C. Kershaw (*Chemical and Metallurgical Engineering*, February 15, March 1, 1919, vol. 20, pp. 176–178, 241–245) reviews the whole question of coal economy from the standpoint of boiler-house practice. The systematic testing of all waste gases and the use of automatic gas-testing apparatus are advocated, and descriptions are given, in this connection, of CO_2 recording appliances such as the Sarco, Uehling, Simmance and Abady, Cambridge bi-meter and auto- and mono-recording instruments.

A report has been published (*Illinois University: Engineering Experiment Station*, 1918, Circular No. 8) dealing with the economical use of coal in railway locomotives.

II.—*COAL.*

Composition of Coal.—M. C. Stopes (*Paper read before the Royal Society*, December 12, 1918) discusses the composition of banded bituminous coal. Four differing substances or constituents compose such coal, namely, fusain (mineral charcoal), durain, clarain, and vitrain, the three latter names being given for the first time. These are recognisable by differences in their macroscopic appearance and texture, by their different behaviour when treated with different chemicals, by differences in the debris of each, left over from their treatment with chemicals, and by the differences in microscopic sections of untreated samples of each.

Oxidation of Coal.—R. V. Wheeler (*Transactions of the Chemical Society*, December 1918, vol. 113, pp. 945–955) gives an account of work carried out for the Mining Association of Great Britain and at the Home Office Experimental Station, on the oxidation and ignition of coal. The results, which are fully reported, largely confirm the observations of earlier investigators.

Geology of the Lancashire Coal-Field.—Hickling (*Paper before the Manchester Geological and Mining Society*, February 4, 1919 ; *Colliery Guardian*, vol. 117, February 14, 1919, pp. 363–364) describes the results of his research work on the geology of the Lancashire coal-fields.

Cannel Coal.—Sir A. Strahan (*Memoirs of the Geological Survey ; Special Reports on the Mineral Resources of Great Britain*, 1918, vol. 7, Part I., pp. 46–58) describes the occurrences of cannel coal in the United Kingdom.

Lignite in England.—Sir A. Strahan (*Memoirs of the Geological Survey ; Special Reports on the Mineral Resources of Great Britain*, 1918, vol. 7, Part I., pp. 1–23) describes the occurrences of lignite in Great Britain. Lignite rarely occurs in this country in sufficient development to be mined. Lignite from the clay-pits near Corfe Castle has been used as fuel by the workpeople, and a trivial amount of lignite has been dug from some seams in the Bracklesham Beds in the Isle of Wight. In the Tertiary beds of Bovey Tracey in Devonshire, lignite attains a greater development than in any other locality in Great Britain, and has there been used as a fuel since the early part of the eighteenth century, chiefly for domestic purposes, but also to some extent in the adjoining potteries. The result of analyses of samples of Bovey Tracey lignite, taken from different portions of the beds, was as follows :

	Lignite from Heap, Air-dried.	Lignite from Seam.
Moisture	14·68	22·97
Ash	6·85	10·80
Coke	42·60	41·90
Sulphur	2·17	2·96
Fixed carbon	35·45	35·13
Volatile matter	42·92	35·13
B.Th.U. (per lb.)	10,534	8,393

Coal in Kent.—A. E. Ritchie (*Iron and Coal Trades Review*, 1919, vol. 98, pp. 35–36, 69–70, 97–98, 172–173, 230–231, 257–258, 289–290, &c.) describes the evolution and development of the Kent coal-field.

Coking Coal in Scotland.—The results of an investigation as to coking coal in Scotland has been presented to the Ministry of Munitions. The report contains tables of analyses, prepared by T. Gray, of coals in Scotland and also analyses of coke.

Coal in Poland.—J. Patrzek (*Glückauf*, May 25, 1918, vol. 54, pp. 325–330), in a general review of the mining and metallurgical industries of the Dombrowa district of Poland, shows a map of the coal-fields of that region, with a list of the companies owning and working the coal. The ownership is chiefly French-Polish. The total output of coal was about 7 million tons in 1913. The coals are non-caking and can only be used in the raw state as fuel.

Coal in Burma.—Sir H. Adamson (*Bulletin of the Imperial Institute*, January–March 1918, vol. 16, pp. 40–79) describes the mineral resources of Burma. Coal is found at Thayetmyo, Upper Chindwin, Shwebo, and Mergui districts, and in the Shan States. The only important attempt to extract coal was made in 1891 in the Shwebo district. The coal was of poor quality and eventually the mine closed down. Upper Chindwin coal is of good quality, but the fields are inaccessible. The amount of coal available in the Chindwin field is estimated at 105 million tons.

Lignite in Asia Minor.—W. Wolff (*Zeitschrift für praktische Geologie*, May 1918, pp. 73–75) describes the occurrence of lignite in Cilicia. Bituminous deposits and seams of lignite are found on the southern slopes of the Taurus Mountains, but their economic value is doubtful. The most important deposit is the bituminous coal-field of Nemrun, forming a shallow basin of an area of about 4 square kilometres. The average thickness of the bed is about 20 inches.

Lignite in the United States.—S. M. Darling (*United States Bureau of Mines*, 1919, Technical Paper 178) deals with the characteristics and utilisation of lignite in the United States. By-products from lignite are obtained in the form of gas, ammonia, oils, and tar. The gas yield is upward of 10,000 cubic feet per ton of lignite, and the gas has a heating value of 400 to 450 B.Th.U. per cubic foot. The ammonia is contained in the gas and gas water; it may be recovered as ammonium sulphate—a valuable fertiliser—as anhydrous ammonia for refrigeration purposes, or it may be treated as a source of other nitrogen products.

III.—*COKE.*

Moisture in Coke.—A. C. Fieldner and W. A. Selvig (*United States Bureau of Mines*, 1917, Technical Paper 148), in their investigations on the determination of moisture in coke, state that the influence of temperature, time, humidity, of drying atmosphere, and fineness of sample on the determination of moisture may be varied over a considerable range without affecting the result appreciably. Oven temperatures ranging from 105° to 200° C. produced a maximum variation in moisture of not exceeding 0·3 per cent. Coke can be dried to " constant weight " without the usually specified preliminary air-drying. The circulation of air dried by sulphuric acid, through the oven atmosphere, as specified for coal analysis, is unnecessary in the case of coke analysis, there being no measurable difference of results between circulating perfectly dry air through the oven and using in the oven the natural air from the room. Moisture can be determined quickly and with adequate accuracy (± 0·5 per cent.) by simply heating to constant weight a large sample of lump coke, in any convenient oven, at a temperature of 100° to 200° C. Because of its simplicity and flexibility this method may be used advantageously at points where coke consignments are sampled.

Coke-Oven Practice.—W. Colquhoun (*Transactions of the Institution of Mining Engineers*, October 1918, vol. 66, pp. 61–79) presents some economic considerations in coke-oven practice. Bee-hive ovens survive, for the reason that they may be started with little preparation and cost when the market is favourable and can be shut down in less favourable times, whereas a by-product plant must be operated continuously, especially if linked up with works for purposes of power supply. Calculations are given as to the saving by the use of surplus gas from regenerative and waste-heat ovens for the generation of power and heating, with notes on by-product oven practice generally.

D. Paton (*Paper read before the Manchester Geological and Mining Society*, April 8, 1919 ; *Iron and Coal Trades Review*, April 18, 1919. vol. 98, pp. 470–471) deals with utilisation of coal for coking and by-product recovery.

Low Temperature Carbonisation of Coal.—W. Savage (*Chemical and Metallurgical Engineering*, October 1, 1918, vol. 19, pp. 579–582) deals with recent progress in coal utilisation and economy. The coalite process and the Smith carbonised semi-coke briquette process are described. The latter is not only highly efficient but gives high-grade recovery products of much economic value. The briquettes are now marketed under the name of " Carbocoal " in America.

F. D. Marshall (*Iron and Coal Trades Review*, February 28, 1919, vol. 98, pp. 251–254) deals with low-temperature carbonisation in relation to the production of motor spirit, fuel oils, smokeless fuel, and power gas. He describes the Tozer retort, which will deal with practically every description of carbonaceous material, caking and non-caking coals, shales, lignites, and peat in every physical condition, from 3 inches down to dust, and will carbonise and produce coke from colliery sludge or washings.

G. W. Traer (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1463–1470) deals with the distillation of Illinois and Indiana coals, and discusses the relative advantages of high and low temperature distillation. With a low temperature distillation plant such coals will yield 12 to 15 per cent. more semi-coke, and double the amount of tar and oil, the value of which is likewise higher per gallon; on the other hand, high temperature processes yield several times as much gas and rather more ammonia.

Coke By-Products.—Modern methods of coke-making and by-product recovery plant and practice are discussed and illustrated by C. Berthelot (*Chimie et Industrie*, October, November 1918, vol. 1, pp. 471–480 and 601–617) with special reference to recent developments in France during the war, and to future economic requirements. The methods employed for the recovery of sulphate of ammonia, tar, and benzol at the Meons plant of the Saint Etienne Coal Company are described in detail, diagrams being given showing schematically the process and the appliances used.

The theory and practice of the recovery of volatile constituents by simple condensation, and by open and closed recovery processes, are dealt with by Ponchon (*Ibid.*, October 1918, pp. 481–491).

Coke-Oven Gas.—R. V. Hollingworth (*Iron and Coal Trades Review*, April 4, 1919, vol. 98, p. 410) deals with the supply of coke-oven gas for town purposes.

Apparatus for Testing Tar.—An apparatus that affords a simple and reliable means of testing the viscosity and consistency of tars is described (*Iron and Coal Trades Review*, April 18, 1918, vol. 98, p. 460).

Reinforced Concrete for Storage Tanks.—F. W. Frerichs (*Chemical and Metallurgical Engineering*, March 1, 1919, vol. 20, pp. 234–236) gives an illustrated description of three large storage tanks, 35 feet inside diameter and 26 feet deep, for the storage of ammoniacal liquors. The walls are 7 inches thick. The capacity of each tank is about 185,000 gallons, and they have been found quite tight and serviceable in practice.

Coking of Peat.—H. Holm has patented a retort and process for coking peat at low temperature (*Echo des Mines*, February 9, 1919, vol. 47, p. 87). The temperature of carbonisation is about 250° C., and the gases, after the removal of the products of distillation, are used for heating the retort and also for drying the wet peat prior to charging. The resulting coke is hard and compact.

IV.—*LIQUID FUEL.*

Search for Petroleum in the United Kingdom.—T. Sington (*Iron and Coal Trades Review*, October 18, December 27, 1918, vol. 97, pp. 427–428, 724) refers to the exploratory work in the Derbyshire coal-field with the object of discovering petroleum. The prospects of finding accumulations of oil are discussed, and it is considered unlikely that liquid oil exists in commercial quantity.

It is reported (*Iron and Coal Trades Review*, June 13, 1919, vol. 98, p. 828) that drilling at Hardstoft has revealed an overflow of oil. It is a true paraffin base oil of very high quality, with 10 per cent. petrol and 40 per cent. kerosene.

Boring for oil, in connection with the Government scheme, is proceeding in two parts of the North Staffordshire coal-field—at Apedale and at Werrington. Considerable work has yet to be done before the decisive stage can be reached, and before proof of the existence or non-existence of oil can be forthcoming (*Ibid.*, June 20, 1919, p. 847).

Sir A. Strahan (*Memoirs of the Geological Survey: Special Reports on the Mineral Resources of Great Britain*, vol. 7, Part I., pp. 41–45) describes the occurrences of mineral oil in the United Kingdom. There are many records of the occurrence of mineral oil in this country, but the importance attached to them has been out of proportion to the quantity of oil obtained or the permanence of the supply.

Kimmeridge Oil Shale.—Sir A. Strahan (*Memoirs of the Geological Survey: Special Reports on the Mineral Resources of Great Britain*, 1918, vol. 7, Part I., pp. 24–45) describes the distribution and characteristics of Kimmeridge oil shale. It has been known for centuries that the Kimmeridge clay contains bands of inflammable shale in Dorset, and for many years that similar material exists in Norfolk, Lincolnshire, and Yorkshire. Until lately, however, no attempt had been made to utilise the material except in Dorset, where a band known as the Blackstone or "Kimmeridge Coal" has been worked at intervals for use by cottagers as fuel, and has been experimented upon for other purposes. The oil obtained by retorting Kimmeridge shales contains from 6 to 7 per cent. of sulphur.

Geology of the Persian Oil-Fields.—H. G. Busk and H. T. Mayo (*Journal of the Institution of Petroleum Technologists*, December 1918, vol. 5, No. 17, pp. 3-33) give an account of their researches in connection with the geology of the Persian oil-fields, controlled by the Anglo-Persian Oil Co., Ltd.

Petroleum in Japan.—J. M. Clements (*Economic Geology*, November 1918; *Mining Magazine*, January 1919, vol. 20, No. 1, pp. 51–53) gives an account of the petroleum industry of Japan. This industry is one of the relatively old industries of the country, although it is only since 1891 that it has been put upon a modern basis. There are five oil districts in Japan proper, situated in the provinces of Echigo, Shinam, Akita, Totomi, and Hokkaido, and one in Taiwan, Formosa. Echigo and Akita are the two large oil-producing districts, producing 99 per cent. of all the Japanese oil.

Petroleum in the Argentine-Bolivian Field.—S. C. Herold (*Bulletin of the American Institute of Mining Engineers*, September 1918, pp. 1503–1522) deals with the economic and geological conditions relating to the occurrence of oil in the North Argentine-Bolivian Field of South America. A belt of seepages occurs in this region which, owing to its remoteness, has not been hitherto much considered by oil operators, while such development as has occurred has, for want of a scientific basis, led to failures. The oil is of high quality; native labour is good, and Government policy is sympathetic towards foreign exploitation. Much further detail remains, however, to be accumulated.

Gas from Oil Wells.—W. R. Hamilton (*United States Bureau of Mines*, 1919, Technical Paper 209) describes various devices for separating and saving the gas from flow and lead lines of producing oil wells. The basic principle of gas trap construction is simple. The mixture of oil and gas is allowed to flow through a chamber large enough to reduce the velocity of the mixture to the point at which the oil and gas tend to separate. The gas, seeking the top of the chamber, is drawn off free of oil; the oil is drawn off at a lower point, and the escape of gas through the oil discharge is prevented.

Petroleum Mining.—D. Hager and G. W. Macpherson (*Bulletin of the American Institute of Mining Engineers*, October 1918, 1621–1627) deal with the conditions which have arisen in the Mid-Continent oil-fields, Oklahoma, where water troubles are being experienced on a scale calculated seriously to alarm operators. In California, where similar troubles have occurred, prompt co-operation on the part of owners has largely overcome them, but so far no such concerted action has been taken in Oklahoma, although the need is exceedingly urgent. Various methods are proposed.

R. O. Neal (*Ibid.*, January 1919, pp. 1–8) discusses the sources of such water troubles, which have to be ascertained before effective remedies for combating them can be introduced.

Liquid Fuel Burners.—An illustrated description has appeared (*Iron and Coal Trades Review*, April 18, 1919, vol. 98, p. 477) of three types of burners designing for burning 50 per cent. liquid fuel mixtures.

V.—*NATURAL GAS.*

Natural Gas in England.—Sir A. Strahan and J. Pringle give a summary of the information available on the occurrence and utilisation of natural gas in England (*Memoirs of the Geological Survey: Special Reports on Mineral Resources of Great Britain*, 1918, vol. 7, Part I., pp. 59–63).

VI.—*ARTIFICIAL GAS.*

Gas-Producers.—An illustrated description is given of the Kerpely revolving grate gas-producer (*Iron and Coal Trades Review*, December 13, 1918, vol. 97, p. 663). It is designed to work on low-grade fuels which cannot easily be treated in a fixed-grate producer.

The new plant of the Smith Gas Engineering Co., Moraine City, Dayton, Ohio, is described and illustrated (*Iron Age*, December 5, 1918, vol. 102, pp. 1373–1378). The firm makes a speciality of a six-section Smith gas-producer capable of gasifying 2 tons of coal per hour, for power and fuel purposes.

Gas-Producer Practice.—J. Seigle (*Bulletin de la Société de l'Industrie Minérale*, 1918, series 5, vol. 14, pp. 79–108) deals with the principles underlying the combustion and gasification of coke, the subject being considered from the point of view that, theoretically, the coke is assumed to possess no volatile matters. The combustion is likewise considered according as water is insufflated or not. The losses by heating, radiation, &c., and balance-sheets and formulæ are given for the practical determination of the economic and technical problems involved.

Enrichment of Producer-Gas.—The enrichment of producer-gas by returning the tar recovered from the gas cleaners to the producer for gasification is briefly described (*Chemical and Metallurgical Engineering*, October 1, 1918, vol. 19, p. 560). The tar is sprayed evenly over a compact fuel bed at a temperature of 1000° to 1200°. If too high a temperature prevails lamp black is produced, which clogs the cleaning system, and if the fuel bed be too cold the liquid saturates the interstices. The use of tar reduces the hydrogen and increases the methane contents of the gas and improves the thermal efficiency of the producer.

Producer-Gas from Low-Grade Fuel.—F. Blache (*Bulletin de la Société de l'Industrie Minérale*, 1919, series 5, vol. 15, pp. 5–28) discusses the question of economising fuel by utilising mine waste and low-grade fuel in gas-producers.

Producer-Gas from Wood.—Leslie B. Williams (*Mining Magazine*, November 1918, vol. 19, No. 5, pp. 246–250) discusses the composition of power-gas from wood, and the methods of obtaining the largest amounts of the most effective components.

Wear and Tear of Large Gas-Engines.—H. Pilling (*Paper read before the Cleveland Institution of Engineers ; Iron and Coal Trades Review*, April 11, 1919, vol. 98, p. 442), in dealing with the installation and working of large horizontal gas-engines, submits data based upon replies received from various firms to questions addressed to them regarding the actual amount of wear and tear noted by them in their large gas-engines.

VII.—*COAL WASHING AND HANDLING.*

Coal Handling.—An illustrated description is given of Barnard's self-discharging grab (*Engineering*, February 14, 1919, vol. 107, pp. 200–202), which is extensively used for discharging coal from ships into barges or trucks. A crane fitted with a 15-cwt. grab can discharge a ship's hold at the rate of 60 to 70 tons per hour.

Coal Washing.—W. H. Graham (*Transactions of the Canadian Mining Institute*, 1918, vol. 21, pp. 231–241) outlines the advantages to be derived from efficient coal washing as reflected in the manufacture of iron and steel.

G. Knox (*Proceedings of the South Wales Institute of Mining Engineers*, January 1919, vol. 34, pp. 291–320) gives an illustrated description of the Draper washer for the separation of fine coal from shale. The principle is based on direct flow, slightly greater than the velocity fall of coal and less than that of the shale, thereby ensuring perfect separation.

Storage of Coal.—J. H. Anderson (*Electric Review*, July 26, 1918, vol. 83, pp. 78–79) gives notes of experiences in the storage of a very large tonnage of bituminous coal, piled in the open. The heap contained about 16,000 tons, covering an area of 46,000 square feet. About fifty vent pipes, 3 to 4 inches diameter, were placed in the heap, and also a number of 1-inch iron tubes for the purpose of taking temperature readings. Readings were taken every day, 90° F. being regarded as a warning temperature. If a source of heat was located, an additional vent pipe was put down which generally arrested the rise of heat. If that failed the spot was trenched.

Coal Briquetting.—J. A. Yeadon (*Transactions of Institution of Mining Engineers*, November 1918, No. 66, pp. 31–34) discusses the economy of briquetting small coal, and the method of manufacture of briquettes. The calorific power of good briquettes is said to be higher than that of the coal from which they are made when pitch is used as the agglomerant.

PRODUCTION OF IRON.

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I.—*BLAST-FURNACE PRACTICE.*

Blast-Furnace Practice.—F. Mulet (*Bulletin de la Société de l'Industrie Minérale*, 1918, series 5, vol. 14, pp. 12–47) gives blast-furnace balance-sheets with a view to getting better economic results by ascertaining just where and how losses take place and how they can be obviated. In specimens given the theoretical loss as dust, &c., in the gases was 4 per cent. of the burthen charged ; in practice it was found to be 15 per cent. While the 11 per cent. difference might be partly accounted for by errors in analysis and inaccurate weighing of the components of the charge, it is still evident that a wide discrepancy exists between theory and practice, and that there is room therefore for considerable improvement in the latter. In the example given there were charged into the furnace, in addition to the usual ore, fuel, and fluxes, a proportion of pig iron, iron turnings, mill-scale and scrap, and the necessary calculations involved in the melting and recovery of such materials are included in the heat balance. The remelting of a ton of pig iron requires in practice 75 kilogrammes of coke, while the recarburisation of oxidised turnings and scale requires 120 kilogrammes per ton. Mill-scale can very profitably be charged, but care must be taken that the bricks and hearth lining are not injured, and that the resulting fusible calcium ferrites do not lead to scaffoldings and accretions.

H. G. Scott (*Proceedings of the Cleveland Institution of Engineers*, 1918-19, No. 3, pp. 120-151 ; *Iron and Coal Trades Review*, January 17, 1919, vol. 98, pp. 67–68) discusses the practical management of blast-furnace plants in Cleveland.

Electric Smelting of Iron Ore.—J. Bibby (*Paper read at the Joint Meeting of the Iron and Steel Institute and the Institution of Electrical Engineers*, May 8, 1919) describes some of the recent developments in the manufacture of iron and steel by means of electric furnaces. The manufacture of pig iron in a blast-furnace requires, on an average, 1 ton of coke per ton of pig iron produced. Given the same ore, an electric furnace would require 0·3 ton of coke per ton of pig iron produced, thus effecting a saving of 0·7 ton of coke per ton of iron. Against this saving in coke must be set the consumption of electrical energy, which averages 0·3 h.p.-year per ton of iron. This means that, other conditions being equal, the costs of the two systems balance when 1 h.p.-year can be obtained for the price of 2·3 tons of coke. The general appearance of the electric reduction furnace follows that of the blast-furnace very closely. The electric shaft furnace is about 30 ft. high instead of 80 ft. as in the blast-furnace. At the point corresponding to the tuyere belt in the blast-furnace the shaft proper of the electric furnace ends, and, in place of the narrow blast-furnace hearth, there is provided in the electric furnace a wide shallow hearth or crucible forming the melting and refining chamber. The necessary heat is generated by the resistance to the passage of current between the electrodes, which project through the roof of the crucible and are embedded in the charge. The larger the furnace, the greater the number of electrodes required to distribute the heat sufficiently, and, since electrodes have not so far been made with a capacity exceeding 20,000 amperes, a number of them are also required to get the desired quantity of energy into the furnace. The smallest furnace commercially is that of 2500 h.p., with an output of 7000 tons of pig iron per year, which has four electrodes, while in a 10,000-h.p. furnace with a yearly output of 31,000 tons of pig iron the number is 12.

In the blast-furnace the temperature of the hearth is fixed by the possible temperature of the combustion at the tuyere zone, say 1800° C., and this determines the melting point of the flux, that is, the possible proportion of lime. But in the electric furnace there is no such limiting temperature, and it is possible to have a flux with a melting point of 2000° C., which permits it to be more basic and therefore more effective as a refining agent. The high temperature in the crucible would be destructive to the roof, even with regular heating, and to avoid this a portion of the outgoing gases is extracted from the main, taken through coolers and dust extractors, and blown against the roof through the free space between the charge and the roof. The gases are cooled to about 70° C., and it is found that if about two-thirds of them are circulated the roof is effectively preserved. At the same time this circulation assists in carrying the heat from the crucible into the shaft, so as to effect the first reduction of the ore at a higher level. Under this arrangement all the gas generated passes, on the average, three times through the shaft, but there is a thermal loss by the amount of cooling necessary.

The author also deals with some of the features connected with the direct arc type of steel refining furnace, and describes two types of furnaces which have been developed on these lines.

A. Stansfield (*Iron and Coal Trades Review*, March 7, 1919, vol. 98, p. 287) reports on the commercial feasibility of the electric smelting of iron ores in British Columbia. He concludes that there is a sufficient supply of ores of a quality well suited to the process and capable of being converted into a high quality of iron or steel, and that there also are available all requisite fluxes, but electric power cannot, at present, be obtained at prices that will permit of the use of the usual electric smelting methods.

R. Turnbull (*Chemical and Metallurgical Engineering*, February 15, 1919, vol. 20, pp. 178–179) reviews the prospects of the electric pig iron industry from the after-the-war standpoint. The question is intimately connected with that of the supply of scrap for steel furnaces, and once the necessary materials can be supplied no difficulty arises in making any ordinary grade of pig iron in the electric steel furnace.

Charging Iron into a Blast-Furnace.—C. T. Wang (*Blast-Furnace and Steel Plant*, March 1919, vol. 7, pp. 125–126) describes the smelting of native Chinese white iron into foundry pig at the blast-furnaces of the Hanyang Iron and Steel Works. The scarcity of pig iron in the Far East, owing to the American embargo on pig iron exports, has led to the use of the cold-blast iron which is made in small blast-furnaces capable of producing from 2 to 6 tons daily per furnace. This iron is unsuitable for foundry purposes, as the sulphur is sometimes as high as 0·125 per cent. and the silicon as low as 0·30 per cent. It has, however, been collected and charged into one of the smaller blast-furnaces at Hanyang, of a capacity of about 100 tons per day. The process is not one of simple melting alone, but seems to involve metallurgical conversion changing part of the combined carbon into graphite, removing sulphur, and increasing the silicon to 2 per cent. Only 10 per cent. of the daily output can be made up by charging iron into the blast-furnace, without interfering with normal working; scrap iron charged together with ore, limestone, and coke descends faster, causing chilled hearth and the production of off-grade iron, and many precautions need to be taken to avoid troubles. The prospects of further developing the process and its economic aspects are dealt with.

The Grading of Pig Iron.—J. Seigle (*Bulletin de la Société de l'Industrie Minérale*, 1918, series 5, vol. 13, pp. 208–243) discusses the views of various authorities as to the causes of the variation of carbon and silicon in blast-furnace pigs, and the relative advantages of grading by fracture and grading by analysis. As both the carbon and the silicon percentages have been proposed as bases for grading by analysis, and as both elements may vary in what, judged by fracture, is one and the same grade, he decides in favour of judging grade by fracture only, as likely, other things equal, to afford the buyer the best notions of what he is buying, and the foundryman the best opportunity of suitably mixing his iron for foundry requirements.

He also deals (*Ibid.*, pp. 245–270) with the relationship between the grade and texture of pig iron and the physical qualities such as tensile strength, ball hardness, and resistance to bending and shock. The texture of low phosphorus foundry irons with from 0·6 to 1·0 per cent. of manganese depends on the silicon and carbon contents and the conditions of cooling, but a given pig iron may assume various appearances according as the cooling has been slow or rapid, and its physical properties will similarly depend on the conditions of cooling. Here again, therefore, the fracture is the best guide, as it corresponds with the cooling conditions and is therefore the safest guide to the physical properties.

Manufacture of Ferro-Manganese.—Comparative data are given showing the saving in manganese that can be effected in ferro-manganese practice by using coke with 8 per cent. of ash instead of a coke containing about 14·5 per cent. ash. (*Iron Trade Review*, December 12, 1918, vol. 63, pp. 1347–1348.)

Blast-Furnace Charging Hoist.—A. Küppers (*Stahl und Eisen*, September 19, 1918, vol. 38, pp. 861–868) describes and illustrates the charging hoist for a new blast-furnace at the Rheinische Stahlwerke, at Meiderich. It is an inclined hoist, with a skip to carry a load of 8·5 tons of ore, or 4 tons of coke, the quantity to be charged daily being about 1200 tons of ore and 500 to 600 tons of coke. The furnace has a capacity of 400 tons of pig iron daily.

Blowing-Engine.—The Snow blowing-engine recently installed at the works of the Parkgate Iron and Steel Company, Ltd., Rotherham, is described and illustrated. The engine is of the twin-tandem, horizontal, double-acting, four-cycle type, with power cylinders 24 inches in diameter, blowing cylinder 59 inches in diameter, and 4-foot stroke. When running at its normal speed of 88 r.p.m. the set is equal to a duty of 25,000 cubic feet per minute, with a discharge pressure of 8 lbs. above atmosphere. (*Iron and Coal Trades Review*, January 31, 1919, vol. 98, pp. 132–133.)

Composition of Blast-Furnace Gases.—J. Seigle (*Bulletin de la Société de l'Industrie Minérale*, 1918, series 5, vol. 14, pp. 109–131) discusses the composition of blast-furnace gases and the volumetric methods of calculating the gas yield and the amount of air used for the blasts. The methods of Grüner and Ledebur are compared, and a new method based on the carbon balance-sheet described. The differences between the results as calculated theoretically and those deduced by actual analyses and measurements of the gases produced in practice are discussed and explained.

Dry-Cleaning of Blast-Furnace Gas.—J. C. Barrett (*Blast-Furnace and Steel Plant*, April 1919, vol. 7, pp. 185–187) refers to the development of a new method of dry-cleaning blast-furnace gas, by F. E. Kling and L. B. Weidlein. The principle of operation is not stated.

Special precautions are taken to retain the sensible heat of the gas, and no water or settling basins are required in connection with the installation.

Electrostatic Separation of Flue-Dust.—H. J. Bush (*Journal of Society of Chemical Industry*, October 31, 1918, vol. 37, No. 20, pp. 389–391 R.) gives a brief account of the Cottrell electrostatic process for the precipitation of flue-dust from waste gases. Various applications of it are mentioned and the apparatus for carrying out the process has been installed at several factories in this country.

O. H. Eschholz (*Bulletin of the American Institute of Mining Engineers*, August 1918, pp. 1293-1306) describes the principles of the process of the electrical precipitation of blast-furnace dust, and the necessary equipment.

Ore Storage at Blast-Furnaces.—The problem of ore storage as dealt with at the blast-furnaces of the Iroquois Iron Company, South Chicago, is described and illustrated by F. L. Prentiss (*Iron Age*, November 28, 1918, vol. 102, pp. 1311–1313). The plant presents numerous features of great interest and includes a car hopper equipped with forced draught heating to prevent the ore freezing during severe winter conditions.

Potash as a Blast-Furnace By-Product.—J. S. Grasty (*Chemical and Metallurgical Engineering*, September 26, 1918, vol. 19, pp. 434–438) deals with potash recovery from blast-furnace dust in America. While such recovery is possible at practically any blast-furnace plant, it is only profitable when the burden contains a fairly high proportion of potassium compounds. In the fluxes and in the coke used these compounds, although fairly uniform, are low, and hence it is to the ore supply that economic results can be looked for. In the United States it is only the Alabama ores that contain relatively high potassium percentages; some of the deposits contain as much as 3 per cent. These are the Cambrian ores. The net profits on such ores, when the Cottrell electric precipitation process is used, could be very high, as much as $12 to $15 per ton of iron produced, which, with a 200-ton blast-furnace would mean $2400 to $3000 per day. A formula for estimating the percentage recovery is given.

A wet process for recovering potash from the dust of cement kilns is described by J. G. Dean (*Ibid.*, pp. 439–447). The product is obtained in an easily handled condition and is readily marketable, while the conditions under which recovery takes place renders the whole process of cement manufacture better and more efficient, the maximum potash recovery coinciding with the maximum cement production.

A bibliography of the whole subject of potash manufacture and recovery for the years 1912 to 1917 is given by F. W. Bruckmiller (*Ibid.*, pp. 447–449).

The Cottrell process for the collection by electrical precipitation of the volatile vapours of alkali salts from blast-furnace dust and cement kiln dust is described by L. Bradley (*Chemical and Metallurgical Engineering*, September 26, 1918, vol. 19, pp. 457–460).

Ironworks in Australia.—An illustrated description is given of the new works of the Broken Hill Proprietary Company near Newcastle, N.S.W. A second blast-furnace is now in course of construction (*Iron Trade Review*, November 14, 1918, vol. 63, pp. 1118–1124). The plant is constructed on modern American principles.

South African Iron Industry.—P. A. Wagner (*Presidential Address to the South African Association for the Advancement of Science; Iron and Coal Trades Review*, April 18, 1919, vol. 98, p. 469), in dealing with the South African iron industry, states that the blast-furnaces already completed are those of the Pretoria Iron Mines, Ltd., and of the Transvaal Blast-Furnace Company, Ltd. The former company propose smelting in a 50-foot furnace a mixture of siliceous and "clay-band" ores. The siliceous ore, an arenaceous ironstone, averages from 40 to 50 per cent. iron and 14 to 22 per cent. silica; sulphur and phosphorus are both very low and titanium is present in traces only.

The clay-band ore averages from 50 to 55 per cent. iron, from 7 to 9 per cent. silica, and from 0·5 to 0·6 per cent. phosphorus. The furnace has a daily capacity of from 12 to 15 tons of pig iron. The Transvaal Blast-Furnace Co., who have erected a 50-foot furnace at Vereeniging in connection with the Union Steel Corporation, intend smelting a very pure bedded magnetite ore, found in the Transvaal Coal Measures, seven miles east of Ermelo. This ore is the purest yet discovered in South Africa, and averages from 66 to 69 per cent. of iron and from 0·5 to 1·5 per cent. of silica. The tonnage in sight, however, is not very great. A third Transvaal company proposes to undertake the production of iron and steel. Two other blast-furnaces which are in course of erection, and expected to be in operation within the next few months, are situated in Natal, one at Wentworth, a suburb of Durban, and the other at Sweetwaters, near Maritzburg. Prospects are very hopeful, as the South African demand for iron and steel is well over 50,000 tons per annum, and is almost certain to increase. The dimensions to which the industry will ultimately attain depend largely upon the success of the efforts that are to be made as soon as practicable at Pretoria to smelt the rich titaniferous magnetites of the Bushveld complex. If these ores could be smelted on a large scale in admixture with the siliceous ores of the Pretoria series, using cheap non-caking Transvaal coal as fuel, South Africa should be able to export iron and steel in competition with the great iron-producing countries of the world.

II.—*SLAGS.*

Slag Cement.—E. Bereslavsky (*Chemical and Metallurgical Engineering*, January 1, 1919, vol. 20, pp. 25–28) deals with the influence of gypsum additions on the strength and setting properties of slag cement made from blast-furnace slags. By a process of elimination he reduces the number of combinations which can usefully be employed to five: (1) granulated slag and lime; (2) granulated slag and gypsum; (3) degranulated slag and gypsum; (4) granulated slag with lime and gypsum, and (5) degranulated slag with lime and gypsum. By "degranulated slag" is meant granulated slag from which all granulating properties have been removed by a preliminary heating up to a high temperature and a subsequent slow cooling in a closed kiln. Cements from blast-furnace slag cannot be accepted or rejected on the general rules applied to Portland cement. In such cements, in order to ensure Portland cement qualities, there should be at least 2 per cent., and preferably more, sulphuric anhydride (SO_3), and this can be secured by the needful gypsum additions, which would enable much present slag to be employed for making Portland cement, which would otherwise fail satisfactorily to do so.

P. J. Freeman (*Paper read before the American Society for Testing Materials*; *Concrete and Constructional Engineering*, November 1918, No. 11, pp. 585–589) describes tests on concrete in which blast-furnace slag is used as the coarse aggregate. The results obtained so far present a comparison of the crushing tests of air-cooled blast-furnace slag, limestone, granite, trap rock and gravel when used as the coarse aggregate, after 14, 30, 60, 180 days, and 12 months. Tests are still in progress to determine the corrosive tendency of sulphur in slag and the relative strength and durability of slag concrete, with high magnesia and low lime, and with low magnesia and high lime.

The crushing tests were performed on solid cylindrical specimens 8 inches diameter, 16 inches high. Analyses of nine slags are given, of which the following two represent the outside proportions of lime and magnesia:

	No. 1.	No. 2.		No. 1.	No. 2.
Silica . . .	34·35	31·98	Titanium oxide .	0·50	0·30
Alumina . .	13·55	12·25	Lime . . .	45·80	31·75
Iron oxide . .	1·02	2·00	Magnesia . .	1·62	19·43
Manganous oxide .	0·71	0·34	Sulphur . .	1·51	1·23

The crushing strength of slag concrete made from these slags was as follows:

	No. 1. Lbs. per Sq. In.	No. 2. Lbs. per Sq. In.		No. 1. Lbs. per Sq. In.	No. 2. Lbs. per Sq. In.
After 14 days .	2134	2206	After 180 days .	4154	4309
„ 30 „ .	2657	2653	„ 12 months .	5028	4885
„ 60 „ .	3306	3403			

B. Neumann (*Stahl und Eisen*, October 17, 1918, vol. 38, pp. 953–960; Abstract in *Génie Civil*, December 28, 1918, pp. 512–513) presents a study of the system lime-alumina-silica and its relations to blast-furnace slag and Portland cement. Diagrams of the temperature of concentration of the ternary system lime-alumina-silica are shown, and illustrations of a dimensional model of the system are given, on the surface of which the melting points of all the ternary combinations of lime, alumina, and silica are represented.

Use of Blast-Furnace Slag for Reinforced Concrete.—J. E. Stead (*Proceedings of the Cleveland Institution of Engineers*, 1918-19, No. 1, pp. 12-78) considers the use of blast-furnace slag for the manufacture of reinforced concrete. A table shows the analyses of the bulk of the slags made in the Middlesbrough district. An account is given of the experience of slag cement users at Middlesbrough and recent literature on the subject of slag cement is reviewed, with notes on the manufacture of concrete from slag. The general conclusion is that blast-furnace slag is an ideal material for use in making reinforced concrete.

E. H. Lewis (*Journal of West of Scotland Iron and Steel Institute*, 1918–1919, vol. 26, pp. 8–16) refers to the groundless prejudice which exists against the use of slag cement, or iron Portland cement, for reinforced concrete. After granulation, roasting, and grinding, the percentage of sulphur works out at 1 per cent., which corresponds to 2·50 per cent. of SO_3, as against 2·75 per cent. allowed in the British Standard specification. At least half the sulphur in iron Portland cement is in combination as sulphide, while in ordinary Portland cement it exists mainly as a sulphate. Various records of tests of iron Portland cement and examples of its use in reinforced concrete construction are given.

Effect of Manganese in Slag as a Fertiliser.—J. S. McHargue describes experiments made to test the effect of manganese on the growth of wheat (*Journal of Industrial and Engineering Chemistry*, April 1919, vol. 11, pp. 332–335). In suitable dilution manganese is found to stimulate the growth and increase the size and nitrogen content of the grain.

III.—*PUDDLING.*

History of the Puddling Process.—C. H. Desch (*Paper read before the Staffordshire Iron and Steel Institute*, February 8, 1919; *Iron and Coal Trades Review*, February 14, 21, 1919, vol. 98, pp. 191–192, 229) gives an account of the evolution of the puddling process. Reference is made to early methods for producing malleable iron direct from the ore and to Cort's invention of the puddling process in 1784, improvements on which were made by Samuel Rogers of Nant-y-Glo, in 1818, and by Joseph Hall of Tipton in 1830. Since that date the details of the process have undergone scarcely any appreciable change. The process depends entirely on skilled manual labour, and the difficulty of finding a supply of suitable labour has long been felt and has been greatly aggravated of late.

The proposals for the improvement of the puddling process fall into two main groups. Those of the first group aim at relieving the skilled puddler of the most laborious part of his duties, and making a choice of workmen from a larger reserve of labour possible. The proposals of the second group aim chiefly at the improvement of the thermal efficiency of the process, usually by replacing direct firing with coal by gas firing, or by the more economical utilisation of waste heat.

The first mechanical rabble of which any record can be found is that patented by K. E. Schafhäutl in 1836, which was tried at the Tividale Ironworks, Dudley. Modifications in the method of working mechanical rabbles were afterwards made by a number of inventors, such as Isaac Hazlehurst, A. V. Newton, Morgan, Griffiths, Dumeny and Lemut, Bennett, Dormoy, Nasmyth, and others.

In the second, and much more important class of improvements, the agitation, instead of being effected by mechanical rabbles, is brought about by the movement of the hearth of the furnace. The earliest design for a furnace of this type is due to an unknown inventor, whose drawing was made at Dowlais Works, certainly before 1834. The drawing shows a pan-shaped iron hearth, rotating on a vertical axis, and making a gas-tight joint with the furnace casing by means of a water seal. It is of great historical interest, especially in view of the renewed interest in rotary puddling at Dowlais some thirty-five years later under Menelaus. The machine which, until the Dowlais drawing came to light, was regarded as the first rotary puddler, is that devised in 1853 by Walker and Warren.

. In May 1868 Samuel Danks began his experiments at the Cincinnati Railway Works. He at first erected two small furnaces, taking from 2 to 3 cwt. per heat, and in the next two years increased the size, the company replacing all its hand puddling furnaces by the rotary pattern. The Danks furnace was adopted in 1871 by a number of American firms, and aroused so much interest that the Iron and Steel Institute, a committee of which had been formed to investigate the possibilities of mechanical puddling, decided to send out a special commission to the United States to examine the working of the Danks process on the spot. This commission, consisting of Messrs. George J. Snelus, John A. Jones, and John Lester, made an extremely thorough investigation of the whole process. The members took with them to America a sufficient supply of the ores and fettlings most used in this country, as well as of pig iron, in order to ensure that any favourable results obtained were not due to the special properties of American raw materials. They kept complete diaries of all the experiments, and weighed the materials and products, also bringing home specimens of the products for testing. Their report, together with supplementary papers by the members individually, was presented in 1872, and was highly favourable to the process. The lining was found to stand well, provided that an anhydrous ore low in silicon was used in making it. The one defect of the process as carried out in the American works, noticed by several experts, was that the fuel consumption was large in the preliminary stage of melting. Subsequent experience has confirmed the opinion that rotary furnaces are not being put to their best use when used for melting pig, and that they should be supplied with liquid metal, either directly from a blast-furnace or mixer, or from a cupola.

FOUNDRY PRACTICE.

Standardisation of Foundry Practice.—S. W. Wise (*Paper read before the British Foundrymen's Association*, November 30, 1918; *Foundry Trade Journal*, February 1919, vol. 21, pp. 95–97) deals with the standardisation of foundry practice, and discusses the variable factors governing cupola operations.

Cupola Practice.—P. R. Ramp (*Iron Age*, April 11, 1918, vol. 101, pp. 946–948) deals with troubles encountered in cupola practice owing to the difficulty of obtaining fuel of uniform quality. The keeping of the cupola itself in good maintenance and repair is very important; the lining should be seen to daily and all slag clinging to the walls removed, even if in so doing a brick or two be sacrificed. Daubing should not be too thick or it will crack off. The preparation of the sand bottom and the technique of the taphole are dealt with. Extra coke beds must be used to offset poor fuel, and uniform charging is a great help to uniform working, as pockets can thereby be prevented. Charging machines have proved valuable adjuncts in foundry practice.

Steel Foundry Practice.—D. D. MacGuffie (*Paper read before the British Foundrymen's Association*, November 1918; *Foundry Trade Journal*, February 1919, vol. 21, pp. 85–89) describes the manufacture of steel castings by the crucible, Tropenas, Stock oil-fired converter, and electric furnace processes.

C. M. Campbell (*Proceedings of Steel Treating Research Society*, July 1918, vol. 1, No. 10, pp. 7–20) describes small converter practice in the manufacture of steel castings. Converter metal always contains a higher percentage of oxides than either open-hearth or electric furnace metal, hence the loss of manganese and silicon per ton is greater. As deoxidisers manganese and silicon are comparatively slow under the best conditions, and cannot do their work to the extent of producing sound castings. In any case the recarburiser should be added molten in order to conserve as much heat as possible and promote rapid action. To finish the work left undone by these elements, a final addition, either of ferro-carbon, titanium, or aluminium, is made in the ladle or in the stream of metal from the converter to the ladle, which is held five minutes to allow the reaction to be completed. The moulding sand is a high-grade silica sand with grains of such size and shape as to maintain the correct porosity and bonding power. The correct mixing of the sand and fireclay in proper proportions is of vital importance. Some notes on methods of casting and heat treating the castings are given.

E. R. Swanson (*Blast-Furnace and Steel Plant*, November 1918, vol. 6, pp. 455–456) gives notes on steel foundry practice in producing army ordnance steel castings, with some reference to physical properties and composition of the three principal grades of steel castings for the United States Ordnance Department.

R. F. Flinterman (*Iron Age*, May 30, 1918, vol. 101, pp. 1398–1399) deals with "reversed duplexing" in electric steel furnace practice, with special reference to the production of small castings. Two furnaces are used, one with a basic lining, as a feeder, and one with an acid lining to finish in. This may, however, be omitted and methods speeded up. Charging, done on a system whereby higher wages are paid the shorter the time and *vice versa*, has improved the time basis. Certain changes in furnace construction have also been carried out. The results now obtained have been so satisfactory and economical that the suggested reversed duplexing has been postponed in favour of the methods now described.

Large Steel Castings.—Sir R. Hadfield, in an address to the Faraday Society (*Iron and Coal Trades Review*, February 7, 1919, vol. 98, p. 161), refers to the production of large steel castings. As an instance, he described a particular application, namely, hydraulic cylinders for cotton baling presses, which are now being produced successfully. The cylinders, cast of steel and not forged or pressed in any way, are of a particularly difficult nature, in some cases running up to lengths of over 30 feet.

Electric Steel Foundry in America.—Practice with a Booth-Hall electric furnace for foundry work is described by C. Lundberg (*Iron Age*, December 26, 1918, vol. 102, pp. 1563–1569). The furnace is at the works of the Avery Company, Peoria, Illinois. It has a rated capacity of 1½ ton and makes five heats per twelve-hour day. The furnace is operated basic, and the magnesite lining is carried up to the roof, which is of silica brick. A little ferro-manganese and ferro-silicon are added before tapping, and a little aluminium is added to the ladle. The plant also comprises four Whiting cupolas for grey iron and semi-steel castings.

Semi-Steel Shells.—An illustrated account is published of the methods of moulding, casting, and machining semi-steel shells (*Iron Trade Review*, November 28, 1918, pp. 1229–1237).

Instructions issued by the United States Ordnance Department for the manufacture of semi-steel shells are abstracted as a guide to manufacturers (*Iron Age*, November 28, 1918, vol. 102, pp. 1317–1321). They give details of the chemical requirements, the cupola operations, core making, moulding, and cleaning.

Briquetting of Steel Turnings.—A. Harrison (*Transactions of the Manchester Association of Engineers*, 1917–18, pp. 409–419) deals with the briquetting of metal turnings and borings, and describes the practice at the works of Tweedales & Smalley, Limited, of Castleton.

Patterns.—J. Horner (*Foundry Trade Journal*, February 1919, vol. 21, pp. 90–94) discusses the leading principles which control the production of patterns and moulds for engine cylinder castings.

Preparation of Foundry Sand.—H. B. Hanley (*Iron Trade Review*, October 17, 1918, vol. 63, pp. 891–894) considers the effect of varying the proportions of the ingredients in mixing foundry sands, the reclaiming of sand by using selected plastic clay and the advantages of the muller type of mixer. The mullers should be carefully adjusted so as not to rest on the pan, otherwise the material may be ground to a powder and the grain size and grade of the mixture will be altered. In using green sand facings containing sea-coal, the percentage of coal should not exceed 6 per cent., otherwise the bond may be seriously weakened.

Mixing Foundry Core Sand.—R. Grimshaw (*Iron Age*, October 3, 1918, vol. 102, p. 807) discusses the various methods in use for securing maximum porosity and strength in cores. The requirements also include infusibility, firmness, and ease in shaking out. An aggregate —or sand—should therefore be used which will leave as large interstices as possible among the particles to be bonded.

Manufacture of Cast Steel Chain.—A. E. Crockett (*Proceedings of the Engineers' Society of Western Pennsylvania*, 1919, vol. 35, pp. 1–25) describes the casting of steel anchor chain in sand moulds. For connecting the links two processes were tried, both of which were found to be satisfactory. One consisted of pouring the entire chain from one heat into previously prepared and united moulds by filling one interlinked mould impression after another. In the other, half the links comprising a complete length of chain were cast separately, shaken out, cleaned, inspected, and made ready for incorporation into finished chain. Subsequently these links were placed into mould cavities and coupled up into continuous chain by pouring metal into other moulds containing impressions for similar links interlinked with the pre-cast chain. Details of the tests subsequently applied are given.

Casting Iron Piston Rings.—E. F. Cone (*Iron Age*, October 3, 1918, vol. 102, pp. 801–807) deals with the special difficulties met with in manufacturing iron piston rings for automobile and air plane engines. No less than 200,000,000 such rings are now made annually in the United States, and by the De Lavaud process, 18,000 to 20,000 can be made per eight to ten hour shift by centrifugal casting in a special machine. The hot metal is introduced into a rapidly revolving permanent mould when it centrifugalises against the outer surface, solidifies, cools, and after removing is annealed and its inner surface ground on another special machine. The composition of the metal which is melted in a very small cupola approximates to the following:

	Per Cent.
Total carbon	3·292
Silicon	2·065
Sulphur	0·061
Manganese	0·437
Phosphorus	0·772

The tensile strain values are very high, and the coefficient of elasticity is in the neighbourhood of 21,000,000 lbs. per square inch, but the elastic behaviour of the rings as cast centrifugally and sand-cast rings differs, and the ultimate resilience of the former is three times that of the latter. The Brinell hardness of the machine-cast rings is 177, whereas that of the sand-cast rings is 241, or 36 per cent. higher.

Castings used in Ship Construction.—B. Shaw and J. Edgar describe the casting of special ship castings, such as rudders and rudder posts, including the making of the templates, patterns, cores, and moulds (*Foundry Trade Journal,* November 1918, vol. 20, pp. 579–584 and 635–640).

Malleable Cast Iron.—T. Turner (*Journal of the West of Scotland Iron and Steel Institute,* 1917-18, vol. 25, pp. 285-302) contrasts British and American practice in the manufacture of malleable cast iron, and discusses the theory underlying both processes. He predicts that in the future the black heart process will be the prevailing one in use both in the United Kingdom and in America.

H. E. Diller (*Paper read before the American Foundrymen's Association; Iron Trade Review,* December 19, 1918, vol. 63, pp. 1414–1416) describes experiments conducted to determine the time necessary for annealing malleable cast iron. The results lead to the belief that annealing can be carried out in forty-eight hours, using a continuous car-type heating furnace.

Accidents in Foundries.—C. C. Sherlock (*Iron Age,* November 21, 1918, vol. 102, pp. 1262–1263) deals with the causes of accidents to workmen from molten metal in foundries, their prevention, and the various aspects of employers' liability and the obligation to provide safety appliances and instruct the workman how to avoid danger. Such accidents as occur are due mostly to water or moisture in moulds, and to rust, moisture, or dust causing explosions of molten metal.

PRODUCTION OF STEEL.

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I.—*PROCESSES OF STEEL PRODUCTION.*

Acid Bessemer Practice in America.—R. S. McCaffery (*Blast-Furnace and Steel Plant*, March 1919, vol. 7, pp. 140–146) discusses American acid Bessemer practice from the special standpoints of the chemistry of the manganese oxidation blow and the elimination of "spitting" by temperature control during the blow. After investigating the theory of the reactions and the thermal data, he concludes that the $2Mn + O_2 = 2MnO$ reaction is not reversible at temperatures possible in a Bessemer converter, as many blows were finished at 1820° or 200° C. above normal temperature, and in these blows the manganese was completely oxidised. In other blows in which residual manganese was formed the silicon in the pig was always high and always residual with the manganese, the explanation being that the early and middle parts of the blow were carried on at a high temperature, causing the manganese carbide to stay behind in the metal and reduce silica. "Spitting" can be reduced or entirely eliminated by temperature control during the blow. For this purpose the steam line into the converters experimented with was increased in size, because scrap was not available to add to the hot charge to lower its temperature. By steaming during the manganese blow, and thus keeping the temperature down, the manganese carbide is burnt out early, its detrimental reducing action prevented and "spitting" stopped.

Basic Steel Manufacture.—The Davies process of eliminating the impurities in the basic steel process is described (*Journal of the Iron and Steel Trades Confederation ; Foundry Trade Journal*, October 1918, vol. 20, pp. 541–542). The bath is lined with a layer of highly heated slag of a rich, limey, and oxidising nature, which slowly liquefies when the molten pig iron is poured upon it and works up through the bath, continuing its oxidising action when floating on the surface. In this process the manganese content of the original pig iron does not matter, as deoxidation is of no account until the finishing period. Increased yield and economy in additions are claimed for the process.

Manganese Alloys in Open-Hearth Practice.—S. L. Hoyt (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 279–289) deals with the use of manganese alloys in open-hearth practice from the point of view of economy and efficiency. The manganese specification should be omitted except in cases where the amount of manganese present in the finished steel has some definite bearing on the properties or heat treatment of the steel. When, therefore, only casting and rolling-mill practice are involved the manufacturer should be allowed to use his own judgment as to the amount of manganese required. It has been estimated that this alone would save 54,000 tons of 80 per cent. manganese per annum in the United States. The use of manganese-silicon alloys is also discussed from the points of view of acid open-hearth, electric furnace, and basic open-hearth practice.

Deoxidation of Steel by Ferro-Manganese.—A. L. Feild (*Journal of Industrial and Engineering Chemistry*, March 1919, vol. 11, pp. 242–245) discusses the theory of the deoxidation of steel by ferro-manganese. Samples of severely over-oxidised steel, and of the same metal, to which ferro-manganese and ferro-silicon had been added, have been found to have the same oxygen content. Present knowledge regarding the true function of ferro-manganese, ferro-silicon, and other deoxidisers is insufficient to explain the contradictions with the current theory of deoxidation which have been established by the experiments of several investigators.

Deoxidation of Steel by Silico-Manganese.—G. Sirovich (*Metallurgia Italiana*, September 1918, vol. 10, pp. 353–357) discusses the use of silico-manganese as a deoxidiser in steel-making. A great economy in the consumption of manganese can be effected by using silico-manganese containing 50 to 60 per cent. manganese, 22 to 25 per cent. silicon, and 20 per cent. iron for the refining of ordinary commercial steels; and the advantage to the Italian industry is that silico-manganese can be manufactured from the abundant domestic mineral supplies of low-grade manganese ores, whereas for high-grade ferro-manganese the ores have to be imported from India.

Repairing Steel Furnace Stacks.—The stacks of some pit furnaces at the works of the Pittsburg Crucible Steel Company, which were badly corroded by gas, have been repaired by building reinforced self-supporting shells around them, a cement gun being employed for the work. A framework of reinforcing steel rods was first bolted to the outside of the stack, and a special cement, called gunite, was applied at the rate of 20 to 25 feet a day. The stacks were 125 feet high and 6 feet diameter at the top. To cover one stack 1100 cubic feet of finished gunite was required. Except for a few days, the stacks were kept in constant operation during the progress of the work. (*Blast-Furnace and Steel Plant*, October 1918, vol. 6, pp. 399–400.)

Water-Cooled Equipment for Open-Hearth Furnaces.—W. C. Coffin (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 497–515) describes water-cooled devices for open-hearth furnaces, mostly on the Knox principle, including doors and frames, tilting furnaces and ports. The Neeland water-cooled buck-stay is also described. Coolers are now also used in the bulk-head that forms the back wall of the gas uptake. Diagrams and details are given of the Knox gas and air-reversing valve. In all these devices care is required that water should not be wasted. It should have a leaving temperature between 170° and 180° F.

Gas-Reversing Valve.—A new Wellman-Seaver-Morgan gas-reversing valve is illustrated and described (*Blast-Furnace and Steel Plant*, March 1919, vol. 7, p. 132). It is similar in principle to the Foster valve, the operating mechanism being outside the casing. The advantages claimed for it comprise rapid reversibility, compactness, and small space. The weight of the hood is counterbalanced by the weights of the lever arm in such a way that the hood is in balance in any position.

Steelworks Equipment.—F. Somers (*Paper read before the Staffordshire Iron and Steel Institute*, January 11, 1919; *Iron and Coal Trades Review*, January 17, 1919, vol. 98, p. 70) deals with the handling of materials at iron and steel works.

Electric Furnaces of Special Type.—A. Sahlin (*Paper read at the Joint Meeting of the Iron and Steel Institute and the Institution of Electrical Engineers*, May 8, 1919; *Iron and Coal Trades Review*, May 9, 1919, vol. 98, p. 618) describes a new type of electric furnace, designed with a view to embodying the advantages of both the direct arc and the free-burning arc types, while avoiding as far as possible the disadvantages of both. The furnace is built of heavy steel plates as a circular ladle with contracted top and dished bottom. The bottom is made up of a layer of coke dust and tar rammed in, supporting double layers of brick. On top of this is rammed and fixed in successive layers a hearth consisting of burnt dolomite and tar for basic operation, or of ganister for acid. Supported and resting on the firebrick, outside the hearth, is placed a circular lining backed by a heavy insulating layer of asbestos sheets and formed of circle-bricks laid with ground joints and thin mortar. This lining may be made of magnesite brick for basic process or of silica brick for acid process. In the lining are placed on the same vertical lines two holes for each pair of electrodes. On top of the contracted top of the side lining rests a dome-shaped roof built of acid or basic brick and fitted in a circular steel frame, which can be quickly removed by a crane and replaced by another pre-heated roof held in readiness.

Graphite or carbon electrodes are used, of cylindrical form, and are extended as they are burnt away by screwing a new section to the rear end of the electrode in operation. The number of electrodes proposed varies from one pair for a furnace hearth up to 3 ft. 6 in. in diameter to six pairs for a hearth from 9 feet to 11 feet in diameter. Direct or single phase current is used for a one-pair furnace, two phase for a two-pair, and three phase for a three-pair furnace, while when there are more than three pairs groups of two pairs are coupled in parallel. If the furnace is to be used for melting and refining steel, the furnace is first heated by the free-burning arc, the electrodes are drawn back and the charge put in. The electrodes are then advanced again. Numerous momentary arcs are formed between the upper electrodes and the charge, but as the latter is melted away in the vicinity of the electrodes the regular free-burning "broom" arc is formed, the radiation and reflection caused by it being most effective for rapid melting. As the bath is formed, this kind of arc reaches only the slag-covered surface of the metal, and there is but little circulation in the interior. The free-burning arcs are therefore now broken by the retirement of the lower electrodes and a direct arc is formed by advancing the upper inclined electrodes towards the surface of the slag, the result being a rapid circulation in the bath and direct transfer of heat to the metal.

W. K. Booth (*Paper read at the Joint Meeting of the Iron and Steel Institute and the Institution of Electrical Engineers*, May 8, 1919 ; *Iron and Coal Trades Review*, May 9, 1919, vol. 98, pp. 617) describes the Booth-Hall electric furnace. The design of this furnace, which is built single, two or three phase, to suit varying conditions, is based on the employment of a solid hearth which becomes conductive of electricity when hot, and of an auxiliary electrode which acts as a return for the current until the hearth becomes heated and conductive. The auxiliary electrode is so arranged that it can be lowered so as to press with its whole weight on top of the charge, and consequently no arc can form underneath it. When the hearth becomes conductive the auxiliary is withdrawn from contact with the charge.

In making steel for the ordinary grade of steel castings the furnace has been worked with a power consumption as low as 446 kilowatt hours per 2000 lb. of steel poured, but the average will be between 500 and 550 kilowatt hours per net ton for continuous operation.

A description is published (*Blast-Furnace and Steel Plant*, November 1918, vol. 6, pp. 443–445) of the method of operation and equipment of a 2-ton Héroult furnace, chiefly producing nichrome. The power for the furnace is furnished in the form of two-phase, 60-cycle, 2200-volt current, transformed to 110 volts by two transformers of the oil-insulated self-cooled type. A Thury regulator automatically maintains an approximately constant current at the furnace electrodes, each electrode having a separate regulating mechanism and a raising and lowering motor.

W. H. Easton (*Electrical World*, August 17, 1918, vol. 72, pp. 295–297) also describes the working of a 2-ton Héroult furnace at the works of the Driver Harris Company, New Jersey, for the manufacture of nichrome and nickel steel. The metal constituents are charged cold into the furnace. The furnace is automatically regulated, and as soon as the charge becomes hot the average power consumption is held nearly constant by the regulator, though the actual power consumption fluctuates widely and rapidly, owing to short-circuits between the electrodes and the charge. The power curve is more irregular with nickel steel than with nichrome. The temperature in the furnace averages about 1200° C.

H. Etchells (*Journal of the Birmingham Metallurgical Society*, March 1919, vol. 7, Part III., pp. 125–142) deals with the function of the electric furnace in modern engineering practice, and gives a brief classification of the various types of electric furnaces.

The Relation of Electric Steel Furnaces to Central Power Stations.—The number of electric steel furnaces in the United States is given at about 300 (*Chemical and Metallurgical Engineering*, January 15, 1919, vol. 20, pp. 73–76). Most of these are located in small and medium-sized steel foundries, and the extension of such plants is dependent on adequate and cheap electric power supply. Electric steel-smelting operations make, however, very varying demands on power supply, and the loads become very heavy during the working of a heat. For this reason it may be feasible to arrange for heats to be made during the night hours when the peak loads are smaller, or in any case to avoid working heats when the load factors for power use for other purposes are high.

Electric Steel Furnace Practice.—R. G. Mercer (*Paper read before the Joint Meeting of the Iron and Steel Institute and the Institution of Electrical Engineers*, May 8, 1919; *Iron and Coal Trades Review*, May 9, 1919, vol. 98, pp. 609–611) deals with the operation and output of various types of electric furnaces in the United Kingdom under actual working conditions.

There are installed, or being installed, 141 electric furnaces with a total capacity of 112,000 k.v.a. Of these, 24 are, or will be, used for Swedish substitute, cupro nickel, alundum, manganese copper, and ferro alloys. The remaining 117 are electric steel furnaces having a total charging and k.v.a.-capacity of 384 tons and 98,769 k.v.a. respectively, and a total nominal output of 31,170 tons per month, based on five days a week, four weeks per month. Assuming that all these furnaces are working at full load, the total nominal output at the end of a year would be 405,000 tons.

As regards the type and nominal monthly capacity of the steel furnaces there were 45 Heroult furnaces (13,760 tons), 27 Electro-Metals (6740 tons), 26 Greaves-Etchells (5680 tons), 6 Snyder (1200 tons), 5 Stobie (2600 tons), 4 Rennerfelt (730 tons), 2 Stassano (240 tons), and 2 "Special" made by the user (280 tons).

The author gives a number of tables, compiled from returns furnished to the Ministry of Munitions, showing the comparative performance of the same or different types of electric furnaces working as nearly as possible on the same class of steel and under similar conditions. In the author's opinion the tilting gear and general arrangement of electrode feed gear in certain types have not been designed to withstand the conditions in a steelworks. Water-cooled collars at the electrode entrance in the roof have been a source of constant trouble and delay. The author disapproves of the water-cooled electrode-holder, regarding its use as an admission that it is exposed to the hot gases coming through the roof at the electrode entrance, which, therefore, has no suitable economiser or seal, or that it has not proper electrical contact round the electrode. One of the great difficulties experienced with large furnaces is due to thermal expansion and contraction of the parts, and to the cost of repairing and replacing the heating units.

J. Lonergan (*Chemical and Metallurgical Engineering*, March 1, 1919, vol. 20, p. 245) deals with the elimination of phosphorus and sulphur in electric ferro-manganese furnaces. Attempts to smelt a high phosphorus ore by using an excess of lime failed to give good results, the ferro-manganese steel containing 0·6 per cent. of phosphorus, but by mixing sufficient low phosphorus ore no trouble was experienced. Tables are given showing an elimination of 47·6 per cent. of phosphorus, of which 31·4 per cent. was carried off through the ventilators. Most of the loss appears to be mechanical and due to the volatilisation of phosphorus; 98 per cent. of the original sulphur was also eliminated.

J. Escard (*Revue Générale des Sciences*, July 15, 1918, vol. 29, No. 13, pp. 401–413) gives a general review of practice in the refining of steel in the electric furnace. The main features of the following furnaces and their methods of working are described: the Héroult, Stassano, Rennerfelt, Girod, Keller, Chaplet, Nathusius, a special induction furnace designed and in use at the works of Saint Jaques, de Montluçon, the Hiorth, and the Röchling-Rodenhauser.

F. J. Moffett (*Paper read before the Staffordshire Iron and Steel Institute*, November 9, 1918) outlines the recent development of the electric steel furnace.

V. Stobie (*Paper read before the Joint Meeting of the Iron and Steel Institute and the Institution of Electrical Engineers*, May 8, 1919; *Iron and Coal Trades Review*, May 9, 1919, vol. 98, pp. 618–620), in dealing with large electric steel-melting furnaces discusses a number of points, including wiring and shapes of furnaces, arc phenomena, transformers, and methods of economising electrodes.

H. A. Greaves (*Paper read at the Joint Meeting of the Iron and*

Steel Institute and the Institution of Electrical Engineers, May 8, 1919; *Iron and Coal Trades Review*, May 9, 1919, vol. 98, pp. 621–622) deals with the application of electrical energy to the melting of metals.

Manufacture of High-Speed Steel.—F. B. Lounsberry (*Proceedings of Steel Treating Research Society*, 1918, vol. 1, No. 10, pp. 24–32) discusses practice in the selection of raw materials for high-speed steel and the methods of manufacture.

T. L. Thorne (*Proceedings of Steel Treating Research Society*, 1918, vol. 1, No. 11, pp. 33–43) describes the procedure in the manufacture of high-speed steel tools. Analyses of typical high-speed steels are given.

Electrodes for Steel Furnaces.—J. A. Holden (*Foundry Trade Journal*, October 1918, vol. 20, p. 537) compares the amorphous carbon electrodes made in Great Britain during the war, with imported American amorphous electrodes. In joining them a paste is necessary, in contradistinction to graphite electrodes, which can be machined, and best quality Ceylon plumbago mixed with hot anhydrous tar is an excellent material for this purpose. The method of jointing is described.

A translation of an illustrated article from *Stahl und Eisen* (1912, vol. 32, p. 1857) has appeared (*Chemical and Metallurgical Engineering*, August 15, 1918, vol. 19, pp. 179–184) dealing with the selection, mixing, and firing of materials for the manufacture of electrodes for metallurgical electric furnaces, and their testing. A bibliography of technical and patent literature is appended.

Electrode Annealing Furnace.—An illustrated description is given (*Iron and Coal Trades Review*, January 24, 1919, vol. 98, p. 103) of a gas-fired furnace for annealing electrodes. The heating chamber is arranged to accommodate six electrodes at a time, of sizes up to 22 inches in diameter.

Manufacture of Ferro-Alloys.—J. Escard (*Revue Générale des Sciences*, December 15, 30, 1918, vol. 29, pp. 673–680, 706–713) describes in detail the manufacture of the ferro-alloys in common use in steel-making and in the production of special steels. The alloys dealt with are ferro-chrome, ferro-silicon, ferro-manganese, ferro-vanadium, ferro-molybdenum, ferro-titanium, ferro-tungsten, ferro-aluminium, and ferro-nickel. The manufacture of all these in the electric furnace is considered, and notes of the properties and uses of the products are given.

J. W. Richards (*Chemical and Metallurgical Engineering*, September 28, 1918, vol. 19, pp. 501–504) deals briefly with all the industrial ferro-alloys, including those containing manganese, silicon, aluminium, chromium, tungsten, molybdenum, vanadium, titanium, boron, and uranium. But little is as yet known of the properties of the two last-named alloys, ferro-boron and ferro-uranium, and much further research work is required.

The use of pure manganese for making alloys in which iron would be detrimental, and for which ferro-manganese cannot therefore be used, is briefly noted and discussed by A. F. Braid (*Bulletin of the American Institute of Mining Engineers*, November 1918, pp. 1697–1698).

J. W. Evans (*Transactions of the Canadian Mining Institute*, 1918, vol. 21, pp. 154–161) describes the manufacture of ferro-molybdenum at Belleville, Ontario. Ferro-molybdenum, made directly from concentrate, was first produced commercially in Canada at Belleville on March 23, 1916. The concentrates were mixed with lime and coke and charged, without previous roasting, into an electric furnace. The furnace charge varies with the grade of the concentrate. A 75 per cent. MoS_2 concentrate, carrying 9 per cent. of iron, will yield a 70 per cent. ferro, if the charge is made up as follows:

	Lb.
Concentrate	100
Lime	120
Coke	10
Scrap steel	5

Production of Tungsten.—J. L. F. Vogel (*Paper read at the British Science Guild Exhibition*, August 30, 1918; *Mining Magazine*, January 1919, vol. 20, No. 1, pp. 12–17) describes the properties and uses of tungsten and methods of production.

Zirconia and Zirconium in Metallurgy.—L. Bradford (*Paper read before the Birmingham Metallurgical Society; Foundry Trade Journal*, November 1918, vol. 20, pp. 596–597) deals with the metallurgical uses of zirconia as a refractory and of zirconium as an addition to steel. Certain alloys have been made containing up to 60 and 90 per cent. of zirconium. Some of the ternary and quaternary alloys with zirconium display useful properties of resistance to oxidation and to chemical action. Ferro-zirconium is said to have been used in Germany in the manufacture of armour-piercing shell and bullet-proof shields. Zirconium steel is said to have displayed extreme hardness, having three times the value of ordinary armour plate.

Manufacture of Ferro-Cerium.—A. Trillat (*Bulletin de la Société d'Encouragement*, Jan.-Feb. 1919, vol. 131, pp. 60–63) reports on the creation of a new industry in France, the manufacture of ferro-cerium. The cerium is chiefly obtained from monazite sands, and together with a little lanthanum and didymium is electrolysed from residues from which the thorium has been extracted. It is partly purified and then melted with iron in the proportions of 30 per cent. of iron and 70 per cent. of cerium, and run into thin rods for the "flints" of lighters, for which its marked pyrophoric properties render it specially suitable.

It is also used for alloying special steels. Such cerium steels are manufactured at present at many of the large French ironworks.

R. Vogel (*Zeitschrift für anorganische Chemie*, March 15, 1917, vol. 99, pp. 25–49; *Science Abstracts*, A, April 30, 1919, vol. 22, pp. 187–188) deals with the manufacture and properties of cerium-iron alloys of varying compositions.

II.—*CASTING AND TREATMENT OF INGOTS.*

Sand Casting of Ingots.—W. L. Booth (*Metal Trades, San Francisco*, October 1918; *Iron Age*, November 7, 1918, vol. 102, pp. 1139-1140) describes the casting of steel ingots, destined for forging, in sand moulds. The ingots can be of large dimensions, up to 16 feet, cast in octagonal moulds 34 inches in diameter, and weighing over 18 tons. The advantage of sand moulds is that sand having a low conductivity does not abstract the heat so rapidly, and the entire mass of steel therefore solidifies at a more uniform temperature than when cast in metal moulds. Such ingots are remarkably free from pipe.

J. E. Fletcher (*Paper read before the Staffordshire Iron and Steel Institute*, December 19, 1918) deals with mechanical methods used for the production of solid steel ingots. The Harmet, Illingworth, Robinson, Rodger, and Talbot systems are described in detail. The author, in his general conclusions, points out that the study of this subject brought into prominence the all-important question of mass-heating and cooling, and its influence on the crystalline structure of steel. Further, if the chemical analysis was unsuitable, included gases, whether in the free state or occluded, were inevitably present. The only really sound steel was a freely piping one, and to obviate the loss attending the formation of pipe, either hot feeder heads or some mechanical method for eliminating the pipe, or a combination of the two, must be adopted. The feeder head applied to an ingot cast in a sand mould produced a coarsely crystalline interior inseparable from slow cooling from the molten state. This was the weakness of a feeder-head ingot, for though the later reheating for forging or rolling would break up the crystalline structure, it would not destroy entirely the original crystal boundaries.

FORGING AND ROLLING-MILL PRACTICE.

Rolling-Mill Design.—W. H. A. Robertson (*Journal of the Birmingham Metallurgical Society*, January 1919, vol. 7, Part I., pp. 9–18) discusses the mechanical design of rolling-mills.

Rating of Rolling-Mill Motors.—K. Pauly (*Blast-Furnace and Steel Plant*, October 1918, vol. 6, pp. 411–414) refers to the difficulties of users of large rolling-mill motors owing to the difference in the manufacturers' ratings of their special types of motors. It is suggested that motors should be rated on continuous capacity at some particular temperature.

American Rolling-Mills.—The two new plate mills of the Brier Hill Steel Co., Youngstown, Ohio, are described and illustrated (*Iron Age*, December 19, 1918, vol. 102, pp. 1521–1524). They occupy the largest mill building in the world, consisting of two aisles each 104 feet wide and 960 feet long. One aisle houses the 84-inch mill and the other the 132-inch mill, the former consisting of two stands of rolls set in tandem and the latter of one three-high stand. Power is obtained outside, at 60-cycle 3-phase 66,000 volts and reduced in 3500 k.v.a. transformers to 2200 volts. The 84-inch mill is driven by a direct current reversing motor of 1,000,000 foot-pounds-feet tongue and the 132-inch mill by a 5000 horse-power wound rotor induction motor.

Electrically-Driven Rolling-Mills.—The conversion of a tinplate mill driven by a slow speed horizontal engine to electric drive is described (*Iron and Coal Trades Review*, March 7, 1919, vol. 98, p. 293).

J. T. Sturtevant (*Paper read before the American Association of Iron and Steel Electrical Engineers*, September 11, 1918; *Iron Age*, October 24, 1918, vol. 102, p. 1016) describes the lay out, equipment, power consumption, tonnages and capacities of eleven electrically driven rolling-mills at the Lehigh plant of the Bethlehem Steel Company. Special emphasis is laid on proper flywheel equipment in such mills, as a means of economising energy consumption and enabling smaller motors to be installed.

An illustrated description is given (*Iron and Coal Trades Review*, March 14, 1919, vol. 98, p. 311) of a 19,000 horse-power reversing rolling-mill motor, which has been recently built for driving a 36-inch roughing and finishing mill. The motor comprises three units rigidly coupled together and mounted on a combined bedplate. The total of 19,000 peak load h.p. is obtained at speeds ± 60/140 r.p.m. The pressure across the armatures is 1400 volts.

Plate Turnover for Tandem Mill.—A novel form of plate turnover installed at the Youngstown sheet and plate mill, is described (*Blast-Furnace and Steel Plant*, March 1919, vol. 7, pp. 128–129). It consists of a series of turning cradles or forks placed between the table rollers and mounted on rack beams actuated by pinions mounted on a common driving shaft. The forks are V-shaped and pivoted at the closed end, the open end or top of each fork being connected by flexible links to stationary pins in such a manner that when the fork is in an upright position in the centre of the table the links on both sides of it are taut.

Rolls for Planished Bars.—The manufacture of chilled rolls for cold rolling is described by L. Garand (*Bulletin de la Société d'Encouragement*, March-April 1919, vol. 131, pp. 329–330). It is practically a new industry so far as France is concerned, and has been developed during the war, prior to which all such chilled rolls, and all shears and other accessories to cold rolling came from Germany, mostly from the vicinity of Düsseldorf. In spite of the initial difficulties the industry has been successfully launched, and at the Lyons fair in March 1917 a complete planishing mill by French makers was exhibited, and up to the present no less than 300 pairs of rolls have been supplied, with all accessory plant and machinery for making planished bars.

Sheet Iron Manufacture in South Russia.—L. Pletsch (*Stahl und Eisen*, December 5, 1918, vol. 38, pp. 1126–1134, &c.; *Iron and Coal Trades Review*, February 14, 1919, vol. 98, p. 201) gives an account of the iron sheet industry of South Russia. The well-known roofing sheets form four-fifths of the whole output. Such sheets are rolled by nine works in South Russia. Formerly they were produced exclusively as black sheets, but in the last fourteen or fifteen years a gradually increasing proportion of galvanised sheets has been used. The tests for roofing sheets are severe. The Railway Administration tests one sheet in every 200 to 400. One test consists in folding the sheet up flat like a handkerchief and unfolding it, and no rupture or hole at the double fold must result.

Manufacture of Strip.—The manufacture of hot-rolled and cold-rolled strip at the mills of the Weirton Steel Company, Virginia, is illustrated and described (*Iron Trade Review*, October 24, 1918, vol. 63, pp. 961–964).

Black-Finishing of Iron and Steel.—E. S. Whittier (*Metal Industry*, 1918, vol. 16, pp. 509–510) discusses the most suitable processes for black-finishing iron and steel on large scale production.

Reheating Furnaces.—G. T. Hagan (*Proceedings of the Engineers' Society of Western Pennsylvania*, 1919, vol. 35, pp. 31–57) describes a design of heating furnace intended to meet the following conditions: (1) Continuous heating from a charge temperature of about 500° F. to wash heat. (2) Avoidance of contact between billets, and a single handling. (3) Ability to effect repairs without interfering with the furnace operation.

An illustrated description is given (*Foundry Trade Journal*, March 1919, vol. 21, pp. 169–170) of a reheating furnace fired on the new "Revergen" principle by means of town gas. It is claimed that this furnace utilises a much larger proportion of the total heat available in the gas than has hitherto been possible.

Electric Reheating Furnace.—W. S. Scott (*Paper read before the Association of Iron and Steel Electrical Engineers; Iron Age*, June 27, 1918, vol. 101, pp. 1676–1677) advocates the use of electric furnaces for heating forgings, as the rate of heating is not only under control but is capable of wide variation. As a resister silicon carbide is strongly recommended. The neutral atmosphere of an electric furnace obviates oxidation. Also, as the conditions are all controllable, it is possible to reduplicate results in actual practice.

FURTHER TREATMENT OF IRON AND STEEL.

Influence of Forging on Specific Density of Steel.—H. E. Doerr (*Bulletin of the American Institute of Mining Engineers*, January 1919, pp. 79–81) has made a number of experiments in order to ascertain whether forging influences the specific density of steel, and finds that while spongy or porous steel is undoubtedly greatly compressed or consolidated by forging, there is little or no change in the density of a steel initially free from cavities. In small ingots the ratio of volume to superficial area is so great that it is doubtful whether they can properly solidify without microscopic cavities being formed. With larger ingots this ratio is smaller, and the percentage of increase in specific density of forged specimens would be reduced to a negligible value if not eliminated altogether.

Case-Hardening.—T. G. Selleck (*Proceedings of Steel Treating Research Society*, March 1918, vol. 1, No. 8, pp. 18–22) gives notes on the chief sources of faults in the carbonising process and the remedy.

Shimer Case-hardening Process.—J. W. Richards (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 431–433) describes the Shimer case-hardening process, which case-hardens by immersion of the material in a bath of fused salts. Melted potassium cyanide or melted sodium cyanide are the most frequently used, either pure or mixed with salts, which lower the melting point when processes of this kind are adopted. For these poisonous and dangerous materials the Shimer process substitutes salts which give off no poisonous fumes and are far less costly than the cyanides, fresh calcium cyanamide being used in a non-case-hardening mixture of melting composition, such as sodium, calcium, or barium chloride. A lively evolution of gas takes place in the molten composition, and the material is then plunged into it. Certain precautions, which are described, have to be preserved. On removal from the bath the case-hardened substances are quenched in cooling liquid of suitable nature in the ordinary way. The case-hardening is quite satisfactory.

Heat Treatment of Tool Steels.—S. N. Brayshaw (*Paper read before the Birmingham Metallurgical Society*, March 27, 1919; *Iron and Coal Trades Review*, April 4, 1919, vol. 98, p. 408) deals with the heat treatment of tool steels, and the prevention of hardening cracks.

Heat Treatment of Steel for Gears.—G. A. Richardson (*Iron Age*, June 27, 1918, vol. 101, pp. 1668–1670) deals with material suitable for cast steel gears and with its heat treatment. He also discusses the relative advantages of case-hardening and oil-hardening. Generally speaking, however, he prefers cast iron to steel for gears, as they are easier to mould, come out cleaner, and require less machining. For specially severe service large size gears of nickel chrome are suitable, such gears being air-hardened. They last longer than cast iron gears, but this is not the only reason for their superiority, as their use obviates breakdowns and so causes saving. Oil-hardened gear is to be preferred to case-hardened, for steady uniform wear. Oil-hardening is also cheaper than case-hardening.

Heat Treatment of Metals used in Aeroplane Construction.—F. Grotts continues his series of articles on the metallography and heat treatment of metals used in aeroplane construction, and deals with brazing and the relative strength of brazed and welded joints (*Chemical and Metallurgical Engineering*, October 1, 1918, vol. 19, pp. 583–587).

Selection and Treatment of Steel.—A reprint is published of the paper by J. F. Keller (*Proceedings of Steel Treating Research Society*, March 1918, vol. 1, No. 8, pp. 28–44) dealing with the selection and treatment of steel, the phenomena of crystallisation, the effect of reheating, soaking and rolling, the effect of shear or compression, the spark method of selecting steels, and the effect of forging. (The paper was originally published by the Society, March 1917.)

Colours of Tempered Steel.—A. Mallock (*Proceedings of the Royal Society*, August 1918, vol. 94, pp. 561–566) shows that the tempering colours of steel cannot be accounted for by the assumption that they are examples of the ordinary interference colours of thin plates, otherwise a reduction of the thickness of the film would cause a change of colour. It was found that the intensity of the colour decreased as the film became thinner but its character remained the same. The tempering colours are best seen by polarised light and their intensity is greatest at the angle of maximum polarisation. It would appear that temper colours are due to some form of selective opacity depending on damped molecular periods comparable with the wave period, rather than on a structure comparable with the wave length.

Application of Surface Combustion to Heat Treatment Furnaces.—J. H. Bartlett (*Proceedings of Steel Treating Research Society*, 1918, vol. 1, No. 11, pp. 18–32) gives an account of experience in applying surface combustion to heat treating and similar work. In surface combustion the heat is generated by the use of explosive mixtures of gas and air, and its application requires a special type of burner and method of control. The proportioning of the gas and air mixture requires particular care, and two forms of proportioners have been designed for the purpose. The one is a low pressure inspirator operating with air at about one pound pressure and gas at the usual low distribution pressure. The other is a high pressure inspirator using gas under pressures of one to ten pounds, which entrains free air for combustion, this arrangement being the simpler one. The burner which has been found to give most satisfaction is of the impact type, consisting of a single large discharge nozzle which throws the mixture downward at a high velocity on a bed of loose refractory material. The refractory bed rapidly comes to incandescence, giving off intense radiant heat. A number of furnace installations are illustrated and described. At the Midvale Steel Company's works, two furnaces, fired with city gas, turned out seven 330-lb. shells each, the average gas consumption being 170 cubic feet per shell. The shells were lowered singly into the furnace and brought to 900° F. in about nine minutes.

Heating and Annealing Furnaces.—W. Trinks (*Blast-Furnace and Steel Plant*, February, March, April 1919, vol. 7, pp. 98–101, 134–137, 171–177) continues to discuss heating and annealing furnaces, and deals with speed of heat transmission and required brick surface, and volume required for burning a given quantity of fuel in unit time. Curves are also given showing values for the rate of heat abstraction from the exterior of the furnace, and a method is given for computing values from curves.

A description is given (*Iron and Coal Trades Review*, March 21, 1919, vol. 98, p. 356) of the Wild-Barfield electric steel hardening furnace. The articles for treatment are suspended from an iron wire and placed in the furnace, where they immediately become magnetised by the current of the heating coil. When the steel reaches the point of decalescence it becomes non-magnetic. The loss of magnetism causes the galvanometer to indicate the condition immediately, so that the article is at once removed from the furnace and quenched. This automatic indication ensures that the steel cannot be overheated, and the finest possible grain is thus obtained.

Annealing Pans.—A special form of pressed steel corrugated pan for annealing is described (*Iron and Coal Trades Review*, October 18, 1918, vol. 97, p. 429). The pans are pressed out from a solid piece of best quality steel boiler plate. The flange at the top and the corrugated sides and ends prevent warping, and a dished cover is supplied. The pans are said to last from 200 to 300 hours under fire.

Manufacture and Testing of Springs.—N. E. Hendrikson (*Proceedings of Steel Treating Research Society*, July 1918, vol. 1, No. 10, pp. 39–44) gives an account of the manufacture of automobile springs, which are made of either high carbon spring steel, with approximately the eutectoid percentage of carbon, or of alloy spring steel. The latter class includes chrome-vanadium, chrome-silico-manganese, silico-manganese, chrome-carbon, and chrome-nickel-tungsten. The methods of cambering, tempering, and heat-treating are referred to in detail. The transverse test has been found to be the most satisfactory method of determining the elastic limit. This may be performed in a Brinell machine by mounting on an anvil a suitable cross-piece with V supports, about 10 inches apart. The load causing a permanent set may then be determined, and the stress due to the load can be calculated by the regular formulæ. If the normal physical qualities of any spring steel are once determined by the tensile test machine, the constant for converting Brinell hardness to ultimate strength may be calculated. After that a combination of the transverse elastic limit test and the Brinell test will give the elastic limit and calculated ultimate strength for any specimen of that steel.

C. T. Edgerton (*Chemical and Metallurgical Engineering*, December 1, 1918, vol. 19, pp. 762–767) deals with the manufacture and testing of elliptical and coil springs, describing the types of steel alloys used, the methods of testing, formulæ for calculating loads, deflections and torsion, the effect of overstrain and molecular hysteresis. The methods of heat treatment are also dealt with.

Pressed Steel Wheels.—G. E. Thackray (*Iron Trade Review*, October 31, November 7, 1918, vol. 63, pp. 1005–1009, 1067–1070) gives an illustrated account of the manufacture of pressed steel car wheels, describing all the operations in detail.

Manufacture of Shells.—F. B. Swander (*Proceedings of Steel Treating Research Society*, 1918, vol. 1, No. 11, pp. 9–14) gives a description of the manufacture of high explosive shells and detonators from the metallurgist's point of view.

Welding Processes.—L. Jackson (*Paper read before the British Foundrymen's Association*, November 2, 1918; *Foundry Trade Journal*, December 1918, vol. 20, pp. 659–663) deals with the various processes of welding, and gives illustrations showing the structure of the metal in welds effected by different methods. Reference is made to results obtained in the electric welding of naval machinery in United States shipyards, and to the light thrown by various investigations on the comparative value of the leading welding processes.

J. H. Davies (*Paper read before the Institution of Mechanical Engineers; Iron and Coal Trades Review*, February 7, 1919, vol. 98, p. 168) describes some experiments which were carried out on the mechanical properties of various steels when subjected to the strong heat of the oxy-acetylene flame, without being melted, and for the same period of time as might be required for the oxy-acetylene welding of the same sized pieces.

H. Cave (*Paper read before the Institution of Mechanical Engineers: Iron and Coal Trades Review*, January 31, 1919, vol. 98, pp. 137–138) describes the development of the oxy-acetylene welding and cutting industry in the United States.

F. Hazledene (*Paper read before the Institution of Mechanical Engineers; Iron and Coal Trades Review*, February 7, 1919, vol. 98, pp. 168–169) describes the oxy-acetylene welding process.

Electric Welding.—A series of descriptive articles on electric welding and welding appliances is published (*Engineer*, February 14, 1919, vol. 127, pp. 145–146). The various systems of resistance and arc welding are discussed, with notes on the conditions under which the processes are carried out in practice.

O. H. Eschholz (*Electric Journal*, July 1918, vol. 15, pp. 247–250) describes the Slavianoff arc-welding process, which is the most widely used of all the arc-welding processes. In this method the metal rod serves both as electrode and weld filler. A table is given showing analyses of electrodes used in various arc-welding processes and of the metal deposited from the electrode in the weld. A better control of the constituents of the deposited metal is recommended. Refractory tubes on the electrode have been suggested, but it is thought that better results would be obtained with an electrode which would generate an atmosphere of inert gases enveloping the arc.

R. S. Kennedy (*Paper read before the Institution of Marine Engineers*, August 1918) gives some general notes on electric welding practice, with special reference to boiler repairs. Arc-welding is best adapted for work over $\frac{3}{16}$-inch thick, but for thinner work one of the gas-welding systems is more suitable. The iron wire used for the weld must be of very pure material, with preferably a small quantity of manganese. To prevent oxidation and to increase the fluidity of the metal, it is usual to coat the metallic electrode with a flux. The voltage across the arc is about 22 to 25 volts, with an equal steadying resistance, making the voltage at the dynamo terminals about 45 volts. An additional resistance is automatically switched in, when the welder breaks the arc, thus keeping the load on the machine constant. The current actually employed is about 175 amperes.

J. Caldwell and H. B. Sayers (*Paper read before the Institution of Civil Engineers; Iron and Coal Trades Review*, March 14, 1919, vol. 98, p. 322) describe electric welding developments in Great Britain and the United States.

W. S. Abell (*Ibid.*) describes experiments on the application of electric welding to large structures.

J. R. Smith (*Ibid.*) deals with the use of electric welding in ship construction and repairs.

J. A. Capp (*General Electric Review*, December 1918, vol. 21, pp. 947–957) has made experiments on mild steel bars for the purpose of determining the conditions necessary to obtain the best results in electric resistance welding. Different current strengths were used, and the current was held for varying lengths of time, in order to produce welds with a greater or less amount of movement of the metal. The results are set forth in full and are illustrated by micrography.

J. F. Lincoln (*Electrical World*, December 14, 1918, vol. 72, pp. 1119–1120) discusses the respective merits of alternating and direct current for electric welding. The cost of an alternating current welder and its equipment is considerably less than that of a direct current welder, but the comparative labour costs are in the proportion of about three to two in favour of direct current welding.

T. T. Heaton (*Proceedings of the Institution of Mechanical Engineers*, 1919, pp. 49–71; *Iron and Coal Trades Review*, January 31, 1919, vol. 98, pp. 136–137) deals with electric welding. He points out how the exigencies of the war had led to a great development in the use of various systems of welding, and how in some respects electric welding had proved under present circumstances more advantageous than gas welding, because of the difficulty of procuring oxygen and carbide of calcium, necessary in gas-welding processes. The author describes the various systems of electric welding.

Electric Welding with Covered Electrodes.—E. G. Rigby (*Journal of the Engineers' Club of Philadelphia*, October 1918, pp. 472–482) states that welds made using plain iron or carbon rods as electrodes may become brittle or porous through oxidation. The joints made with oxidised metal are particularly liable to corrosion. A covering for the electrodes of blue asbestos yarn has been found effective in preventing oxidation of the deposited metal. In fusing the asbestos acts as a reducing agent and excludes the atmosphere from the metal. The yarn may be coated with silicate of sodium or aluminium to vary the temperature of fusion. Some notes on the operation of covered electrodes are given.

Application of Electric Welding to Shipbuilding.—H. A. Hornor (*Proceedings of the Engineers Society of Western Pennsylvania*, 1919, vol. 34, pp. 641–670) deals with electric welding in shipbuilding, and gives a number of diagrams prepared by the Electric Welding Branch, Education and Training Section, of the United States Shipping Board, Emergency Fleet Corporation, showing types of joint and symbols; principles governing design of welds and position and combinations of types and symbols. The results of careful investigation and severe testing show that with due care electric welding is a perfectly reliable way of joining materials for ship construction, within certain well understood limitations. Results of tests on welded joints are given, and the cost of welding is compared with that of riveting in ship construction, the saving in labour cost being about 60 per cent. in the case of electric welding used in the construction of a standard ship.

C. Henderson (*Journal of the Engineers Club of Philadelphia*, November 1918, vol. 35, pp. 499–501) describes the applications of electric welding at the Submarine Boat Company's yard.

S. V. Goodall (*Ibid.*, pp. 493–498) gives a detailed account of the methods adopted in Great Britain for welding a steel barge and two other vessels and compares them with American methods.

C. A. Adams (*Ibid.*, December 1918, pp. 531–536) summarises the work carried out by the Electric Welding Committee under the auspices of the U.S. Shipping Board. Opinion is divided as to the relative advantages of alternating current and direct current for welding.

An account of the construction of the first steel ship built entirely without rivets is published (*Electric Review*, September 28, 1918, vol. 73, p. 495). The ship was built in a British shipyard and measured 125 feet long, with a 16-foot beam, the displacement being 275 tons. It is estimated that the saving on a ship of this size, using electric welding, is 25 to 40 per cent. of time and about 10 per cent. of material.

Electric welding practice in shipbuilding is illustrated and described (*Iron and Coal Trades Review*, December 20, 1918, vol. 97, pp. 702–703).

Nomenclature for Electric Welding.—H. G. Knox (*Paper read before the Engineers' Club of Philadelphia ; Engineering*, November 8, 1918, pp. 522–526) recommends a uniform terminology for use in electric welding practice. Standard symbols for various types of welded joints are given with illustrated descriptions of the design and types of weld in use.

Tests of Soundness of Welds.—O. S. Eschholz (*American Drop Forger*, November 1918, vol. 4, pp. 448–450) indicates methods of determining the character of arc welds. The most trustworthy indication of the soundness is offered by penetration tests. Of the various liquids that may be applied, kerosene in which a suitable oil soluble dye has been dissolved has marked advantages. When sprayed on to a weld the kerosene is rapidly drawn into any capillaries produced by incomplete fusion between deposited metal and the scarf, and the presence of faults can be detected, which hydraulic pressure and other methods will not reveal.

Path of Rupture in Steel Fusion Welds.—S. W. Miller (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 311–338) deals with fusion welds in material containing not over 0·3 per cent. of carbon. In electric welds a peculiar structure was encountered ; needles or plates in the grains and similar material in larger spots at the grain boundaries, which he believes to be iron nitride, probably containing some carbon. It is this which is probably responsible for the brittleness of electric welds. They appear, but much less often, in oxyacetylene welds, in which they appear, too, to have less effect on brittleness. It is improbable that such films are cementite, as in electric welds the carbon is almost entirely burned out. They might either be nitride or oxide of iron. Rupture invariably follows the path of such structure.

Welding High-Speed Steel.—E. E. Thum (*Chemical and Metallurgical Engineering*, September 15, 1918, vol. 19, pp. 301–308) considers the conditions required in successfully welding high-speed steel tips on to a carbon steel tool, in order to economise in the cost of high-speed steel.

Grinding.—G. J. Alden (*Proceedings of Steel Treating Research Society*, April 1918, vol. 1, No. 9, pp. 27–30) analyses the action of a grinding-wheel in operation. The distinction is shown between the radial or real depth to which the wheel cuts and the depth to which the abrasive grain in the wheel cuts into the material. This latter value is called the "grain-depth of cut," and is the controlling factor in the correct working of the wheel.

Electrolytic Pickling and its Effects on Physical Properties of Steel.—J. Coulson (*Transactions of American Electrochemical Society*, 1917, vol. 32, pp. 237–243) refers to the phenomenon of brittleness in steel springs resulting from acid pickling and electroplating, and states that this effect is avoided by the use of electrolytic pickling. In order to determine the effect of different methods of pickling, samples of spring steel wire were pickled chemically by dipping in acid, and electrolytically by using them as cathodes and anodes. Oscillation tests showed that the chemically cleaned and the cathodically cleaned samples were very brittle, while the anodically cleaned wires had the same resilience as the original samples. Drill bars, hot-rolled and cold-rolled steels were subjected to similar treatment, and the mechanical tests again gave results similar to those obtained with the spring steel, the degree of brittleness induced by chemical and cathodic cleaning being most marked in the case of the high-carbon steels.

Pickling Steel.—E. E. Corbett (*Blast-Furnace and Steel Plant*, December 1918, vol. 6, pp. 497–501) reports the results of an investigation to determine the possibilities of the use of nitre cake as a substitute for sulphuric acid for pickling steel, with a view to conserving sulphuric acid.

Value of Thick and Thin Coatings on Tin-Plates.—A report has recently been published in America of the results of an investigation by a committee, representing the American Sheet and Tinplate Company, the American Can Company, and the National Canners Association, on the relative value of different weights of tin coating for canned food containers (*Iron and Coal Trades Review*, October 11, 1918, vol. 97, p. 402). There has long been a theory that a heavy tin coating was necessary on food containers, and the committee was appointed to make a thorough test of the effectiveness of thick as compared with thin coatings. The conclusion drawn from the investigation is that the value of different weights of tin coating on cans is for all practical purposes the same with average weights of 1 to 3 lb. of tin per base box. It is, however, very difficult to make lighter coated plates of sufficient uniformity with hand-worked tinning machines, and some automatic method of coating should be adopted which will give a uniform coating with a much lower tin consumption.

M. D. Buck (*Chemical and Metallurgical Engineering*, November 1, 1918, vol. 19, pp. 659–660) deals with the question of tin economy in the tin-plating industry, and shows that the usually accepted notions as to heavy coatings being required for food containers are unfounded, and that the value of different weights of tin coatings is practically the same whether one or three pounds of tin be used per base box (112 sheets 14 × 20 inches).

Enamelling of Steel.—At a recent meeting of the American Ceramic Society several papers dealing with the enamelling of metal surfaces were read. Amongst others was one by C. Treischel and L. E. Barringer (*Chemical and Metallurgical Engineering*, February 15, 1919, vol. 20, p. 182) on the cause and control of blistering in sheet steel enamelling. This is usually due to the occluded gases in the steel, but the results obtained in practice can be improved by careful attention to the conditions during pickling.

PHYSICAL AND CHEMICAL PROPERTIES.

The Shear Test as a Method for Measuring the Strength of Cast Iron.—C. Fremont (*Comptes rendus*, December 9, 1918, vol. 167, pp. 949–952) considers that the testing of cast iron by means of separately cast test-pieces is not a satisfactory method, owing to possible differences of conditions, such as the temperature of casting, rate of cooling, or method of moulding. Test-pieces should be taken from the actual casting, and the dimensions should be such that a sample may be taken without spoiling the casting. It is recommended that a small cylindrical piece might be removed with a hollow drill, and as the shear strength is equal to the tensile strength, a shear test should be made on the small sample obtained. The tests are made in a simple machine with ordinary shearing blocks, to which the load is applied by a lever with a sliding weight. The shear test can be made on much smaller masses of metal than are necessary for the tensile test.

Tests of Cast Iron.—H. J. Young (*Paper read before the British Foundrymen's Association*, January 25, 1919; *Foundry Trade Journal*, March 1919, vol. 21, pp. 157–160) deals with the properties of cast iron test-bars, and discusses the production of test-bars and the testing of cast iron.

J. Seigle reports the results of bending tests on steel and cast-iron bars, and reviews the information yielded by a study of the elastic and permanent deformations (*Bulletin de la Société de l'Industrie Minérale*, 1919, series 5, vol. 15, pp. 87–126).

Influence of Heat on Cast Iron.—E. Adamson (*Journal of the West of Scotland Iron and Steel Institute*, February 1919, vol. 26, pp. 80–84) deals with the influence of heat on the structure and physical and chemical properties of cast iron.

Influence of Constituents of Cast Iron.—A. Campion (*Lecture delivered before the British Foundrymen's Association*, February 8, 1919; *Foundry Trade Journal*, March 1919, vol. 21, pp. 164–165) discusses the influence of some constituents on cast iron. A number of experiments were made in order to find the effect of adding to cast iron a definite amount of nickel, chromium, molybdenum, tungsten, boron, vanadium, titanium, and manganese. These constituents were introduced as ferro-alloys, and added to the bottom of the ladle before it was filled with the metal. The pig iron selected was of a quality considered most suitable for work, such as the cylinders for internal combustion engines. Such castings compelled the selection of an iron low in graphitic carbon, because of the fact that iron high in graphite increases in volume on "reheating." The castings were submitted intermittently to a temperature of 450° C. for periods of four hours each. In every case the results showed that the metal went through some remarkable changes, especially during the first six heats; after the sixth heat, however, most of the samples remained fairly stationary. The following table shows the comparative results:

	Transverse Strength in Lbs. on a Bar 1 Inch by 1 Inch on 12-Inch Centres.	Tensile Strength in Tons per Square Inch.
Metal without admixture	2136	13·5
With an addition of 1 per cent. of:		
Chromium	2332	16·05
Nickel	2650	14·75
Boron	2550	14·5
Tungsten	2650	16·6
Molybdenum	2730	17·6
Manganese	2360	14·25

Comparative Value of Cast Iron, Wrought Iron, and Steel Pipe for Drainage Purposes.—W. P. Gerhard (*Journal of the Franklin Institute,* 1919, vol. 187, pp. 99–109) finds from a series of investigations that for drainage purposes extra heavy cast iron soil pipe is satisfactory from the corrosion point of view, but not as regards caulked joints, the screw-thread of welded pipe being superior. Investigation, he claims, leaves no doubt that genuine wrought iron pipe is a far more durable material for house drainage than steel pipe.

Physical Properties of Malleable Castings.—H. A. Schwartz (*Iron Trade Review,* October 17, 1918, vol. 63, pp. 899–904) shows that the characteristics of malleable cast iron recommend it for various purposes for which it has not hitherto been used. The constituents of malleable castings are defined, and the structure of the metal and mechanical properties as revealed by tests are considered.

Definition of Hardness.—R. M. Leslie (*Engineering,* August 9, 1918, vol. 106, p. 153) has carried out experiments with the object of measuring the work required to produce a unit volume of indentation. The unit volume was taken at 1 mm.^{3} and a weight ½ kilogramme falling half a metre was used in each case. The shape of the tool dropped was changed, but the volumes of indentation were found to agree closely. The results of tests on steels of different degrees of hardness are given, and it is suggested that if hardness be defined as resistance to deformation work should be used as the measure of hardness.

Determination of Hardness.—R. G. C. Batson (*Paper read before the Institution of Mechanical Engineers*, October 18, 1918; *Iron and Coal Trades Review*, October 25, 1918, vol. 97, p. 464) discusses the determination of hardness by means of the indentation produced by a static load, and by the impact of a ball or cône. The materials taken for experiment were mild steel, boiler plate, rail steel, high-carbon steel, and cast iron. The hardness numbers obtained with the various indenting tools are summarised in a comparative table.

W. C. Unwin (*Ibid.*) traces the relationship between indentation hardness tests of ductile metals. The variation of the hardness number in the Brinell test, with the load and size of ball, is a rather serious defect, which is due to the fact that the indentations are geometrically dissimilar. P. Ludwik obviated the defect by using a right-angled cone, which gives indentations always geometrically similar. Ludwik prefers to measure the depth instead of the width or diameter of the impression, and defines the hardness number as the load divided by the conical area of the indentation.

C. A. Edwards and F. W. Willis (*Ibid.*) have deduced from experiments a law governing the resistance to penetration of metals which are capable of plastic deformation. This law, which applies to the very soft metals and to hardened tool steel, may be expressed by the equation $d = \mathrm{CE}^{\cdot 35}$, where d equals the diameter of the indent made by a 10-millimetre ball, C equals a constant which varies with the total hardness of the metal, and E equals the total energy of impact. On account of the influence of time, and the varying degree of deformation produced with loads which are gradually increased to a maximum, the Brinell scale is not really satisfactory.

J. G. Ayers, jun. (*Proceedings of the American Society for Testing Materials*, 1918, vol. 18, Part II., pp. 460–477) describes a new method of obtaining Brinell hardness. Instead of using a dead load hydraulically applied, as in the general type of Brinell machine, a definite impact was employed. This impact was obtained by fastening the Brinell ball to the bottom of a given weight and allowing it to drop from a given height on to the test specimen. From the diameter of the impression thus produced, the true Brinell hardness number may be obtained from a conversion table.

Static, Dynamic, and Notch Toughness.—S. L. Hoyt (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 339–351) points out that the occurrence of the notch effect in machines and engineering structures is much more common than is usually recognised. Engine parts reveal an amazingly large number of notches, and material composing such parts should have a high degree of notch toughness to ensure against failure. The only logical test capable of yielding reliable results is the notched-bar test. The Charpy test, by showing low impact value, will serve to detect weakness or errors due to improper heat treatment.

Physical Tests of Rolled Steel.—J. J. Mahon (*Iron Age*, October 31, 1918, vol. 102, pp. 1082–1083) endeavours to account for the variations in mechanical properties of rolled shell steel failing to correspond with variations in chemical composition such as would be anticipated, and concludes that the discordant results are due to precipitation of the ferrite during the heating process. Uneven precipitation leads to the physical properties varying within the same bar. By proper reheating and further rolling the ferrite can be reabsorbed.

J. H. Hall (*Ibid.*, pp. 1084–1086) and E. R. Swanson (*Ibid.*, pp. 1086–1087) deal with kindred subjects and specifications, tests, and heat treatment as applied to ordnance steel and ordnance castings.

Influence of Hot-Deformation on the Qualities of Steel.—G. Charpy (*Revue de Métallurgie; Mémoires*, September–October 1918, vol. 15, pp. 427–448) contributes investigations on this subject, based on those published in the *Journal of the Iron and Steel Institute* (1918, No. II. pp. 7–25), but revised and restated in the light of his latest researches, and with special reference to the nature of the deformation undergone.

Effect of Repeated Stresses.—C. Fremont (*Comptes rendus* January 6, 1919, vol. 168, pp. 54–56) discusses the premature rupture of steel under repeated stresses. It is contended that so long as the stresses set up do not exceed the elastic limit, rupture will never occur no matter how often the stresses are repeated.

Internal Stresses in Steel.—A. Portevin (*Comptes rendus*, 1918, vol. 167, pp. 531–533) deals with the internal stresses set up in steel during rapid cooling and the method of measuring them. This can be done to some extent by determining the internal stresses in thin layers removed in succession by a cutting tool and estimating the changes undergone in the remaining solid. The creation of internal stresses by sudden cooling below conversion temperatures may permit of the separate determination of the stresses resulting from modifications of the state of internal equilibrium and of those due to quenching alone.

Instrumental Indication of Resilience.—F. J. Schlink (*Journal of the Franklin Institute*, 1919, vol. 187, pp. 147–169) deals with the concept of resilience with respect to indicating instruments. The instrumental methods discussed comprise the use of: (1) index and scale instruments; (2) comparison instruments read by reference to a fiducial mark; (3) value-controlling instruments, usually non-indicating; (4) totalising, aggregating, or integrating instruments.

Those chiefly dealt with are the instruments in the first and third categories. It is shown that the area of the hysteresis loop obtained on complete cyclic calibration is a measure of the energy dissipated in the operation of the instrument. To arrive at both regional and aggregate effects of causes producing variance, both the form and area of the hysteresis loop must be observed. Causes of lag are discussed, and it is shown that resiliency determination opens up a field for the type testing and selection of instruments quite distinct from that of ordinary methods of calibration and permits of selection between types of instruments rather than between individual instruments. The more general methods of diminishing variance are indicated.

Stresses in Steel Rails.—J. E. Howard (*Paper read before the New England Railroad Club*; *Engineering News Record*, April 25, 1918, vol. 80, p. 812) shows that stresses up to 8 to 9 tons per square inch may exist in steel rails in the track, when no load is on them. Such stresses are the sum of those due to the cooling of the rail after the finishing pass in the rolls and those resulting from deformation produced by the rolling stock. Compression stresses exist near the surface in the head, while tensile stresses occur along the line of the junction of the web with the head and base. These stresses undoubtedly have to be taken into account in investigating the causes of rail failures.

Effect of Cold Working on Fatigue due to Reversed Stress.—H. F. Moore and W. J. Putnam (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 391–404) deal with the effect of cold working on the resistance of steel to fatigue under reversed stress, undertaken as part of an investigation by the National Research Council Committee on Fatigue Phenomena of Metals. Fatigue stress is defined as the maximum fibre stress that will cause fracture of the material after the repetition of any given number of cycles of stresses, each cycle involving the variation of stress from a minimum to the above maximum. The fatigue stress, then, varies with the number of repetitions occurring in the lifetime of a structural or machine number and with the range of stress for each cycle of stress. It will be lower for a number in which the stress is completely reversed than for one in which the stress varies from zero to a maximum. Tests of cold-pressed steel showed a slight improvement in fatigue strength of a steel after cold-pressing as contrasted with diminished strength after cold-stretching, but this result needs further confirmation. The statement, often made, that steel subjected to reversal of stress will have its life materially increased if allowed resting periods, and that the static elastic strength of overstressed steel is increased by rest, was not borne out by the results of the tests made, details of which are given. The curves showed no marked benefit from a short period of rest on the fatigue strength, particularly for stresses within the limit of proportionality of the material.

Sandberg Sorbitic Process for Treating Rails.—The results of a series of abrasion tests and drop tests on rails treated by the Sandberg sorbitic process are published (*Engineering*, November 29, 1918, vol. 106, pp. 625–629). The plant for treating the rails is illustrated, and a number of micrographs showing the structure of treated rails are given.

Manganese and Open-Hearth Rails.—H. W. Roberts (*Electric Railway Journal*, October 19, 1918, vol. 54, p. 697) gives results of tests made on the Chicago Elevated Railway, which show that the life of manganese steel rails is about seven times as long as that of high carbon open-hearth steel rails on curves of 100-foot radius. The rails were all 80-lb. rails fitted with guard rails.

Transverse-Fissure Rails and High-Phosphorus Streaks.—G. F. Comstock (*Bulletin of the American Institute of Mining Engineers*, November 1918, pp. 1699–1714) discusses the subject of transverse fissure in steel rails and the views held as to their cause, which are usually that they are due to fatigue and not to the quality of the metal, or, alternatively, that the quality of the metal and mill practice are responsible for their occurrence. He has carried out a number of metallographic tests, etching with Stead's reagent, and also making a number of sulphur prints of rail sections, and finds a connection between transverse fissures and high-phosphorus streaks, the nucleus of the fissure being, in many cases, located in the most distinct of the streaks in the rail head or in the uppermost of the distinct streaks. Practically all rails with this type of failure were found on examination to contain these streaks. Also, of the rails examined those rolled from reheated blooms were found much less apt to contain those streaks, due to uneven phosphorus distribution, than direct-rolled rails, while many that gave good service in track, without failure, lacked the streaks entirely. This agrees with Dr. Dudley's experience that rails rolled from reheated blooms do not usually develop transverse fissures, and the natural inference is that this is because they do not contain the high-phosphorus streaks. This affords a good reason and justification for reheating the blooms in the course of rail manufacture, which helps to diffuse the phosphorus.

Cause of Failures in Steel.—In a short address, K. W. Zimmerschied (*Proceedings of Steel Treating Research Society*, 1919, vol. 2, No. 1, pp. 24–29) deals generally with the causes and mechanism of failures in steel, as revealed by examination of fractures.

Monel Metal.—J. Arnott (*Engineering*, October 25, 1918, vol. 106, p. 451) gives notes on the composition and properties of Monel metal. The alloy is produced from the nickel-copper ores of Sudbury, Canada, and in smelting no attempt is made to separate the nickel and copper. The composition of rolled bars averages: Nickel, 66 to 67 per cent.; copper, 29 to 30 per cent.; manganese and iron, 3 to 3·8 per cent.;

and silicon, 0·10 to 0·13 per cent. The cast metal contains a higher proportion of silicon, namely, from 1·2 to 1·5 per cent. Rolled Monel metal shows considerable strength at high temperatures, the following being the results in tons per square inch of tests on eighteen bars, heated in an electric furnace:

	Yield Point.	Tensile Strength.	Elongation per Cent.	Reduction per Cent.
Normal	21·3	41·4	51	69
320° C.	17	38·5	48	62
410° C.	15·6	33·8	49·5	63
500° C.	15·2	28·7	45	56
630° C.	10·4	16·2	33	—
700° C.	7·9	10·3	27	36

Specifications.—The revised specifications for steel rails recommended by the American Railway Engineering Association have been published (*Iron and Coal Trades Review*, April 18, 1919, vol. 98, p. 475).

The standard specifications for iron and steel, and non-ferrous materials of the American Society for Testing Materials, have been published (*A.S.T.M. Standards*, 1918).

Interallied Specifications for Aircraft.—G. Charpy and M. Girard (*Génie Civil*, November 30, 1918, vol. 73, pp. 423–425) review the proposals for uniform specifications, in the allied countries, relating to materials for aircraft construction. The work of unifying the specifications was started in 1918, on the initiative of the British Engineering Standards Association, and has resulted in the completion of twenty-four specifications, each relating to one special material. These cover conditions of manufacture, heat-treatment, and the preparation of test specimens.

Erosion of Guns.—E. Demenge (*Revue Générale des Sciences*, October 30, 1918, vol. 29, No. 20, pp. 579–584) discusses the problem of the erosion of guns of large calibre. Reference is made to the investigations of Fay and to the work of Howe. Fay attributes erosion to the hardening of the surface, as soon as the gun is in use, due to cementation, thermal treatment, and cold-working. Howe finds that hardening is the principal cause, and explains how the hardening is produced and increases with the continued firing of the gun.

The author considers that the most effectual remedy is the employment of a metal which must be as resistant as possible to erosive action. It might be supposed that an alloy of steel with a metal less fusible than itself would best answer the purpose; but molybdenum, titanium, and vanadium, which all have a higher melting point than iron, have the effect of lowering the melting point of iron when alloyed with it. Tungsten raises the melting point, but experiments have shown that tungsten alloys do not satisfactorily resist erosion. Manganese steels used for tube-drawing show a remarkable resistance to wear, and the conditions of tube-drawing resemble very much those of firing a gun—

namely, rapid friction at high temperatures. In view of the low thermal conductivity and specific heat of manganese steel, its capacity to resist wear appears surprising, but these properties are determined, as in the case of all other steels, when the material is in the pearlitic state, and they may have quite different values in the austenitic state, the condition under which the material best resists erosion. The following is the composition of the steel of two captured German guns, one a 4-inch, the other a 6-inch field-gun:

	4-Inch.	6-Inch.
Carbon	0·372	0·430
Silicon	0·199	0·229
Manganese	0·368	0·218
Phosphorus	0·017	0·016
Sulphur	0·025	0·045
Nickel	2·870	2·070
Chromium	1·270	1·350
Copper	...	1·136
Cobalt	...	0·040

The absence of the refractory metals tungsten, vanadium, and molybdenum is noticeable, and the purity of the steel is in remarkable contrast to the impurity of the German shell steel.

Occlusion of Gases in Metals.—A general discussion on the occlusion of gases in metals took place at a meeting of the Faraday Society under the presidency of Sir Robert Hadfield, Bart. (*Proceedings of the Faraday Society*, November 12, 1918). Sir R. Hadfield gave an opening address, in which he reviewed the work of previous investigators, with the addition of notes on the practice of his own firm in the production of sound steel castings, on the occurrence of slag inclusions in wrought iron, and on critical forging temperatures. T. Baker describes some experiments made with the object of ascertaining the composition and volume of gases in steel and their effect on the physical properties of the metal. Cosmo Johns discusses the properties of metals as affected by their occluded gases. H. A. Kent, J. W. McBain, and A. W. Porter present contributions on the theories of occlusion. A. McCance deals with balanced reactions in steel manufacture. After discussing the reactions in the open-hearth process, he refers to the formation of blowholes in steel and to methods for estimating the gas content of steels.

Application of Röntgen Rays to the Examination of Metals.—G. Respondek (*Stahl und Eisen*, September 12, 19, 1918, vol. 38, pp. 837–841, 872–876) considers the physics of the Röntgen rays with regard to their application to the examination of metals. Radiographs of iron and other metals are shown, and the arrangement of the apparatus for obtaining the radiographs is described. The process is thought to be of special use in the examination of reinforced concrete slabs, for the detection of rust on the reinforcing bars and cracks in the cement.

At the joint meeting of the Faraday Society and the Röntgen Society, held on April 29, 1919, a general discussion took place on the examination of materials by X-rays. Sir R. Hadfield gave brief résumés of the work that has been carried out in this country and abroad. These reports all tended to show that with the apparatus at present used it is possible to detect small flaws in steel 2 inches thick. Apparatus has been recently constructed in London, however, with which it is hoped to penetrate steel as much as 9 inches in thickness.

W. H. Bragg, in a brief introductory discourse, explained the rationale of the method.

E. Schneider described the researches carried out in the Schneider Laboratories at Le Creusot, where the apparatus in use permits of the penetration of 40 mm. of steel.

Sir R. Hadfield and S. A. Main gave the results of radiographic examination of carbon electrodes, used in electric steel furnaces.

Sir R. Hadfield, S. A. Main, and J. Brooksbank described the experiments carried out at the Hadfield Research Laboratory on the absorption power of different steels under the X-rays.

Phosphorus Etching Reagent.—K. Harnecker and E. Rassow (*Stahl und Eisen*, November 21, 1918, vol. 38, pp. 1079–1080) show micrographs of specimens etched with Oberhoffer's modification of Stead's etching reagent for detection of phosphorus segregations in steel. Oberhoffer's formula as given by him (*Ibid.*, August 17, 1916, vol. 36, pp. 798–799) is as follows :

Distilled water	500	cubic centimetres
Ethyl alcohol	500	"
Stannous chloride	0·5	gramme
Cupric chloride	1·0	"
Iron chloride	30·0	"
Conc. hydrochloric acid	50·0	cubic centimetres

It has been adopted in many laboratories and gives good results, especially with high-carbon steels.

Heterogeneity of Steel.—H. Le Chatelier and B. Bogitch (*Comptes rendus*, September 30, 1918, vol. 167, pp. 472–477) state that the macrostructure developed in a steel by etching with Stead's copper reagent has been ascribed to heterogeneity in the distribution of the phosphorus. The authors find that it is possible to develop the same structure in steels free from phosphorus, and they suggest that oxygen remaining in solution as FeO is the real cause.

Grain Boundaries in Heat-Treated Alloy Steels.—R. S. Archer (*Bulletin of the American Institute of Mining Engineers*, January 1919, pp. 51–55) describes a method of etching which has been found useful in bringing out the grain boundaries of chrome-nickel and chrome-vanadium steels hardened and tempered to a Brinell hardness of about 300. It consists of etching the specimen in a 4 per cent. solution of picric acid in ethyl alcohol for a period varying from 5 to 25 minutes and then rubbing off the carbonaceous smudge on moist broadcloth or kersey.

Grain Size and Mechanical Properties of Metals.—Z. Jeffries (part 2 *Thesis Submitted to Harvard University* for degree of Doctor of Science; *Bulletin of the American Institute of Mining Engineers*, 1919, pp. 575–578) has investigated the effect of temperature, deformation, and grain size on the mechanical properties of metals, which has been printed in abstract. New light is thrown on the amorphous theory in metals, and the amorphous and crystalline phases of substances are studied in detail.

Welding Mild Steel.—H. M. Hobart (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 517–561) deals with investigations undertaken by the Welding Research Sub-Committee of the Welding Committee of the Emergency Fleet Corporation. The general object was to extend the use of welding in the construction of merchant ships, and to provide a definite basis for obtaining the best economy and efficiency in employing welding in place of rivetting in the construction of the hulls of ships. The possible causes of failure in fusion and spot-welding processes in this connection are explained, and appendices are added giving the standard procedure as laid down by the Fleet Corporation for testing welding electrodes and for Wirt-Jones tests of arc-welded half-inch ship plate.

Alumina Inclusions in Steel.—A. Stadeler (*Stahl und Eisen*, January 11, 1917, vol. 37, pp. 40–41; *Revue de Métallurgie, Extraits*, September–October, 1918, vol. 15, pp. 292–294) deals with inclusions in steel which, in the molten condition, has only aluminium, in excessive quantities, added to it, and the inclusions in which can therefore only be attributed to alumina. Such inclusions are very minute and very hard. They do not tend to merge into one another, but remain as separate particles which resist polishing or break in the process. They are blue-grey, or even black, under the microscope, and do not seem affected by rolling in the same way as, for example, silicate inclusions are, as they do not appear to elongate during rolling operations, but to remain discrete and rounded.

Microstructure of Steel.—B. J. Smart (*Proceedings of the Engineering Association of New South Wales*, 1916–17, vol. 32, pp. 41–74) deals generally with the microscopic examination of steel and the lessons to be drawn therefrom. The paper is illustrated by numerous micrographs.

W. E. W. Millington (*Transactions of the Manchester Association of Engineers*, 1917–18, pp. 189–225) discusses the practical use of the microscope in engineering, and describes the apparatus necessary for ordinary commercial work. He also gives the results of microscopic examinations of certain metals.

J. G. Ayers, jun. (*Proceedings of the American Society for Testing Materials*, 1918, vol. 18, Part II., pp. 88–97) describes the most important metallographic changes occurring in the critical range of steels. The specimen used was a piece of 0·50 per cent. carbon steel which was heated to well above its range and then quenched in water. A number of photomicrographs are given showing every change resulting in the microstructure. The structure shown in each case is briefly described.

Flaky and Woody Steel.—F. Giolitti (*Chemical and Metallurgical Engineering*, March 15, 1919, vol. 20, pp. 271-273) gives his views on the subject of these defects, which were frequently met with in the guns made in Italy for the Italian army. He considers that flakes originate in tender alloy steels as intercrystalline cracks probably intensified by inclusions and segregations. They can therefore be controlled by careful steel furnace practice, casting, soaking, reheating, forging, and heat treatment. At the Ansaldo works pouring is carried out very hot, the ingots are fluted octagons, and the hot steel is cooled to 600° C. in the mould and then stripped and left in the air. The cold ingot is reheated to 1200° C., and forging done at a red heat. The large dendritic crystals in the hot-poured ingots require care and skill in forging, but when rightly done such steel produces superior results. Chromium steel properly made of pure materials under reducing conditions and containing no oxide will never develop cracks. Flaky and woody structure, two defects very closely allied, occur in steel containing highly oxidised inclusions.

C. Y. Clayton, F. B. Foley, and F. B. Laney (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 203–237) describe certain defects, such as flakes and fibrous or woody fractures, encountered in the metallographic testing of many nickel steel gun forgings made for the United States Ordnance Department. The average chemical composition of the steel studied was 0·38 per cent. carbon and 2·9 per cent. nickel, and it was made both by basic electric and basic open-hearth processes. All flaky steel examined microscopically showed unmistakable evidences of overheating, and the areas or grains of sorbite were characterised by a prominent development of the Widmannstätten structure. It is probable that in transcrystalline fracture the path of rupture followed the plates of ferrite that produce the Widmannstätten structure in the grains of sorbite. Under the microscope flaky steel reveals a complete lack of grain refinement, while analysis shows that the flake areas are higher in phosphorus and carbon than the normal metal. The most characteristic effect of flakes is to reduce ductility, tensile strength, and elastic limit. The cause of flakes is ascribed to (1) foreign inclusions; (2) gaseous inclusions and cavities; (3) scale and local decarburisation; (4) segregation of non-ferrous elements; (5) overheating and non-uniformity of heat preparatory to forging; (6) shape of ingot and method of forging; and (7) differential expansion of areas in heterogeneous metal. No. (5) above is regarded by the authors as the most probable cause.

H. S. Rawdon (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 183–201) deals with the causes and the elimination of the defects commonly known as "snowflakes," "flakes," or "scabs." Micrographs are given showing well-marked instances of these defects, together with photographs showing the macrostructure. Examination leads to the view that flakes are discontinuities within the steel, often associated with extremely thin films of slag which are either continuous or formed of tiny isolated globules. Such defects probably originate in the ingot, where they appear as intercrystalline shrinkage cracks. They occur in the cast metal along with the slag inclusions in the angles between the branches of the tree-like dendritic crystals. They persist throughout the history of the forging into the finished form as discontinuities in the metal, often associated with slag films, which have resulted from the working down of the slag inclusions, with which they are associated from the beginning. The coarsely crystalline appearance of the flake is a surface configuration only, and is a record of the crystalline condition—that is, of the dendrites existing in the steel at the time the discontinuity originated. Though they are usually associated with dirty steel, the converse is not true; the fact that the steel is dirty or badly contaminated with slag inclusions is not a sure criterion for condemning the metal as defective because of flakes.

Microstructure of Wrought Iron.—An unusual feature in the microstructure of wrought iron is described by H. S. Rawdon (*United States Bureau of Standards*, 1917, *Technologic Paper No.* 97; *Engineering*, January 18, 1918, vol. 105, pp. 77–79). The ferrite crystals present a mottled appearance after prolonged etching with an acid reagent such as 5 per cent. nitric acid in alcohol, which extends in streaks over the surface of the specimen. This intra-crystalline etch-pattern is quite distinct from the etching pits, which result from prolonged etching of ordinary wrought iron. It is considered to be due to the non-uniform distribution of dissolved phosphorus in the ferrite, the area constituting the mottled etch-pattern being relatively high in phosphorus. By using Stead's cupric chloride reagent the patterns can be more strikingly developed. The fractures in some wrought iron articles which had failed in use, and which showed these features in their structure, ran parallel to the mottled bands, and are considered to have been caused by them, owing to the brittle character of ferrite rich in phosphorus.

Attention is drawn to the slowness of diffusion of phosphorus in ferrite, which accounts for the persistence of the non-uniform structure during the heating and rolling operations undergone by the wrought iron articles before reaching the finished condition.

Microstructure of Tinplate.—L. Mayer (*Stahl und Eisen*, October 17, 1918, vol. 38, pp. 960–962) reports the results of a metallographic examination of tinplate. A strip of tinned charcoal plate, 1 centimetre wide, was covered with a layer of copper electrolytically deposited, polished and etched with 2½ per cent. hydrochloric acid. Under the microscope small elongated tin crystals were visible. The tin showed no signs of combination with the iron, but the thickness of the tin coating showed considerable unevenness.

Microstructure of Iron Deposited by Electric Arc Welding.—G. F. Comstock (*Bulletin of the American Institute of Mining Engineers*, January 1919, pp. 43–49) discusses the identity of the needles or small crystals found in oxyacetylene and electric welds. Such pale crystals typical of steel fusion welds may occur abundantly in iron containing only 0·04 per cent. of carbon, and when annealed thoroughly and cooled slowly they will diffuse into steel from the welded metal, but do not merge with the pearlite of the steel. The conclusion is that they are neither cementite, martensite, or any similar carbide product, but probably nitride of iron. Sodium picrate etching tests fail to differentiate between nitride and carbide or sulphide in polished specimens of steel.

Illumination of Micrographic Specimens.—H. M. Sayers (*Engineering*, December 27, 1918, vol. 106, pp. 729–730) discusses the principles of illumination as applied to micro-metallography. The virtual source of light should be located a tube-length distance from the objective measured along the course of the beam. The practical test of this condition is that the image of the source of light is sharply focused on the object at the same time that the object is seen focused in the field. To obtain the maximum resolving power from the objective, the beam falling on the upper lens from the reflector should approximate two-thirds the diameter of the lens. If the actual light source placed at tube length distances gives too small an image to fill a sufficient proportion of the field for satisfactory observation, a magnified real aerial image of it must be formed at that distance of sufficient area to fill the field. To modify the brightness of the image to suit visual and photographic requirements, use a diaphragm either in the plane of the aerial image or at the auxiliary condenser, not between the objective and the image of the source. For magnifications requiring objectives of shorter focus than ½ inch (12 millimetres) use oil immersion objectives.

Influence of Rate of Temperature Change on Transformations of Alloy Steel.—H. Scott (*Bulletin of the American Institute of Mining Engineers*, February 1919, pp. 157–167) points out that previous investigations show that with the occurrence of a split transformation on cooling alloy steels from increasingly high temperatures: (1) when the higher temperature transformation Ar′ is observed with low values of maximum temperature, troostite, or a decomposition product results, and (2) when the lower temperature transformation Ar″ is observed, with high values of maximum temperature, martensite is the resulting product. His own investigations show that, for a certain alloy, by varying the rate of cooling, the maximum temperature remaining constant, a strictly analogous phenomenon is observed, increasing rate of cooling having the same effect as increasing the maximum temperature. He therefore concludes that (*a*) the Ar′ transformation consists of transformations Ar3, Ar2, and Ar1; (*b*) that the Ar″ transformation consists of the transformations Ar3 and Ar2, and (*c*) that the Ar1 transformation, suppressed when Ar″ is observed, occurs on heating, as Ac_t with an evolution of heat, and the formation of troostite or a coarser condition of the carbide. The maximum of the transformation Ac1–3 occurs at a higher temperature when the previous cooling gave Ar′ than when it gave Ar″.

The A4 Transformation Point in Iron and Silicon-Iron.—A. Sanfourche (*Comptes rendus*, November 4, 1918, vol. 167, pp. 683–685) has redetermined the temperature of the thermal change corresponding with the rapid increase of magnetic susceptibility of iron at 1280° C. discovered by Curie. On heating the temperature was found to be 1365° C., and on cooling it was 1310° C. An addition of silicon to the iron results in lowering the temperature of A4 and in diminishing the intensity of the thermal change, until with 2·5 per cent. silicon it is too small to be determined.

Surface Tension of Liquid Steel.—Cosmo Johns (*Journal of the West of Scotland Iron and Steel Institute*, 1918–19, vol. 26, pp. 36–42) discusses the solid and liquid states of steel. The properties of an optically clean surface of liquid steel are referred to, the surface being similar to that of a polished metallic surface with a vitreous film. Its maintenance is attributed to the presence of an atmosphere of iron vapour. It is shown how the surface tension may be qualitatively determined, the surface tension value varying inversely with the volume of the gases occluded.

History of the Iron-Carbon Theory.—W. Broniewski (*Chimie et Industrie*, June 1918, vol. 1, pp. 55–65) traces the origin and development of the iron-carbon theory through its earliest conception, which was in 1897, when H. Le Chatelier first pointed out the resemblance between steel and saline solutions and introduced the notion of solid solution. In the same year Roberts-Austen constructed the first iron-carbon diagram, to which in 1900 Bakhuis-Rooseboom first applied the phase rule. Theories as to the allotropy of iron commenced with that enunciated in 1888 by Osmond. The subsequent stages of the theory and of the divergent views to which it has given rise are then traced, and a brief statement of the present views is given.

Flame and Furnace Spectra of Iron.—G. A. Hemsalech (*Philosophical Magazine*, September, October 1918, vol. 36, pp. 209–230, 281–296) gives an account of experiments carried out in electric tube resistance furnaces, the results of which show that the spectra of iron given by such a furnace at atmospheric pressure, and up to a temperature of about 2400°, are caused by the action of heat on a chemical compound of the metal and not on the free metal itself. He concludes that the so-called high-temperature furnace spectrum of iron, emitted at temperatures above the boiling point of the metal, is not caused by purely thermal actions, but requires for its emission the co-operation of electric forces. The facts supporting this conclusion are set forth.

Zirconium Steel.—J. Garçon (*Bulletin de la Société d'Encouragement*, January–February, 1919, vol. 131, pp. 148–155) deals with the manufacture and properties of zirconium steel. This alloy is one of quite recent discovery, and little is to be found concerning it in text-books on alloys. The present notes are practically the first to be published. The first patent bearing on the applications of zirconium to metallurgy appear to be British patent 29376, 1910, taken out by Ludwig Weiss. It was then recommended as an addition to castings to improve their soundness, and was intended to take the place of titanium. Its value consisted in its scouring action. Steel alloys containing from 10 to 35 per cent. of zirconium, added in successive small quantities, have been prepared, and have proved of value when added in small amounts to molten steel, so as to approximate to about 1 per cent. in the ultimate metal. A steel with the following composition has been used to make masks:

	Per Cent.
Carbon	0·42
Manganese	1·00
Silicon	1·50
Nickel	3·00
Zirconium	0·34

This steel has been substituted for the nickel-chromium and nickel-molybdenum steels previously used for this purpose. Its resistance to German armour-piercing projectiles of the type K3, in comparison with the resistance of the other steels in question, was found to be in the following proportion:

Equivalent Thicknesses.—16 millimetres chromium-nickel steel = 13 millimetres of nickel-molybdenum steel = 10 millimetres nickel-zirconium steel.

Such a steel requires to be annealed at 875° and cooled in air; then oil-quenched at 840° and oil-annealed for three hours at 180°. It then has a tensile strength of 198 kilogrammes per square centimetre; an elastic limit of 169 kilogrammes and a Brinell hardness of 470. The proportion of zirconium present should not exceed 0·33 per cent.; with 0·5 per cent. the steel ceases to display properties of interest. As zirconium is very readily oxidisable, silicon, manganese, and titanium should be added first to eliminate all traces of oxygen; even then only 25 per cent. of the zirconium added will be found in the alloy. The ferro-zirconium used is obtained in the electric furnace by reduction with aluminium, but should not contain more than 5 per cent. of aluminium, otherwise the tensile strength of the steel will be impaired. In America zirconium steel is being made by the Central Steel Company, Massillon, Ohio. Details of the process and of the nature and composition of the charges made are given; as well as an account of the subsequent rolling and heat treatment of the resulting alloy. At Niagara a new high-speed steel, containing iron-nickel-tungsten and zirconium, is being made to compete with stellite. Notes are given of the methods for estimating zirconium, and for the analysis of alloys containing that element.

Ferro-Zirconium.—H. C. Meyer (*Transactions of the Ceramic Society*, Session 1918–1919, vol. 18, Part I., pp 264–275) refers to the uses of zirconium in the steel industry. Various unauthenticated reports have been circulated as to the remarkable properties of German armour plate, samples of which are said to have been analysed and found to contain zirconium. Krupps were, prior to the war, investigating zirconium, and it is interesting to note that the Brazilian Government reports show that in 1913 there was exported from that country 1119 tons of zirconium ore. As there was no important consumption of the ore at that time in either the United States or England, it is natural to assume that nearly all of this tonnage went to Germany.

One of the most recent alloys of zirconium placed on the market consists of between 40 and 90 per cent. zirconium, with the residue mainly iron or an iron-group metal. Small percentages of titanium and aluminium are also introduced. It is claimed that the alloy is not subject to oxidation, is highly resistant to chemical reagents, and is readily malleable. It is suggested that one of the alloys in this series may find important application in the manufacture of drawn filaments for incandescent lamps. A typical analysis of some of the alloys produced shows: zirconium 65 per cent., iron 26 per cent., titanium 0·12 per cent., and aluminium 7·7 per cent. The production of the alloys is accomplished either by reduction with finely divided aluminium, together with mixed oxides of iron, titanium, or whatever metals it is desired to introduce into the alloy; or they can be produced by heating the mixed oxides in a graphite crucible in an electric furnace, using either zircon or zirkite as a source of zirconium.

Precipitation of Zirconium Phosphate.—G. Steiger (*Journal of the Washington Academy of Sciences*, December 4, 1918, vol. 8, No. 20, pp. 637–639) has made experiments to determine the allowable acidity of a solution in which zirconium phosphate may be quantitatively precipitated, with the object of applying the method to the analysis of rocks containing small percentages of zirconium. The standard zirconium solution used was made by preparing from native zircon the double fluoride of zirconium and potassium. After purifying by repeated crystallisation, it was decomposed with sulphuric acid and the fluoride driven off by heat. Sulphuric acid was added in varying quantities and the zirconium precipitated by the addition of microcosmic salt. As both iron and titanium may be thrown down with zirconium phosphate, the solution should contain the greatest possible quantity of free acid, and the titanium must be kept well oxidised with hydrogen peroxide to prevent it from being precipitated. The results indicate the formation of a basic salt that approaches normal zirconium phosphate, ZrP_2O_7, as the acidity of the solution is increased. The solution may safely contain 3 and perhaps as much as 5 per cent. of free sulphuric acid.

Corrosion Tests of Iron.—R. B. Fehr (*Journal of the American Society of Mechanical Engineers*, October 1918, vol. 40, pp. 829–833) shows that trustworthy results of the relative corrosion of iron and iron alloys may be obtained on small specimens without accelerating the conditions, provided that the same care is taken as is usual in quantitative chemical analysis. The best method of expressing the results is to give the volume of material removed in a given time from each unit of surface. Titanium treated steel shows considerably less corrosion than other steels exposed to tap water and to weak salt solutions. Samples of pure iron and of ordinary steel showed about the same amount of corrosion.

Corrosion of Metals by Acids.—O. P. Watts and N. D. Whipple (*Transactions of the American Electrochemical Society*, 1917, vol. 32, pp. 257–280) describe acid corrosion tests on iron and other metals. The hypothesis previously put forward that polarisation by hydrogen is the cause of the protective effect of arsenic on iron against corrosion by sulphuric acid is confirmed by the facts (1) that the corrosion by acids of iron protected by arsenic is invariably greatly stimulated by oxidising agents, and (2) that arsenic does not protect iron from attack by corrosive agents which evolve no hydrogen by their action.

C. E. Fawsitt and A. A. Pain (*Proceedings of the Royal Society of New South Wales*, September 4, 1918) describe experiments on the behaviour of iron in contact with sulphuric acid. The very slow action of con centrated sulphuric acid on steel is only slightly accelerated by dilution to 85 per cent. acid. The action increases rather suddenly by dilution from 85 to 80 per cent., and again by dilution from 70 to 65 per cent.

Corrosion of Wire Ropes.—W. F. Robertson (*Iron and Coal Trades Review*, March 7, 1919, vol. 98, p. 286) has presented a report on an accident which occurred at a Canadian colliery owing to the breaking of a cable. Dealing with its cause, his conclusions were that the failure of the cable was entirely due to the oxidising of the wires, chiefly internally, caused by apparent lack of any internal lubrication, leaving the wires exposed to the action of a more than normally corrosive water and a humid atmosphere. The internal hemp core, which under a sufficiently effective lubrication system would serve as a reservoir of oil to protect the wires from corrosion, not being supplied with oil, became a reservoir of acid water and so hastened the corrosion of the wires. As an indication that this sort of interior corrosion is not of unusual occurrence, a piece of 1¼ inch of cable from a Sudbury mine was tested at McGill University. It broke at 58,600 lb., whereas the new cable had a breaking strength of about 128,000 lb. This cable showed but little deterioration discernible externally, whereas in the broken end the internal corrosion was excessive.

Corrosion of Concrete Reinforcements.—The failure of reinforced concrete structures to withstand the action of sea-water is discussed by H. J. M. Creighton (*Paper read before the Faraday Society*, July 23, 1918; *Chemical and Metallurgical Engineering*, October 15, 1918, vol. 19, pp. 618–623). A number of instances of such failure are given. To avoid such cases occurring the waterproofing should be carefully carried out, and the Schoop coating process is advocated for this purpose. Painting the reinforcing rods is also recommended. The bearing of the problem on the manufacture of concrete ships is duly considered.

Bureau of Standards, Washington.—G. K. Burgess (*Blast-Furnace and Steel Plant*, March, April 1919, vol. 7, pp. 130–131, 195–197) gives an account of the work of the Bureau of Standards, Washington, and describes the laboratories and equipment.

CHEMICAL ANALYSIS.

Simplified Rapid Method for Carbon Determination.—W. Finkl (*Journal of American Steel Treaters' Society*, January 1919, vol. 1, No. 4, pp. 133–136) describes a rapid method for the determination of carbon. A bulb of the simplest form has been devised, consisting of a single chamber with stopcocks at the entrance and exit, which can be easily wiped dry for weighing. In a single-chambered bulb the absorbent must not only collect CO_2, but must also be a dryer. The absorbent which met these conditions was a physical mixture of c. p. sodium hydroxide and asbestos fibre, and is prepared by grinding fresh dry sodium hydroxide with four times its bulk of ignited asbestos fibre in a porcelain mortar, and after drying it should be placed in air-tight jars for use as needed; 1500 grammes of fine steel drillings are spread in a V-shaped groove made in RR alundum contained in the combustion boat. The CO_2 absorption bulb is connected to the train and the stopcocks opened. Oxygen is passed through the train at the rate of 450 cubic centimetres per minute. After the sample is burnt and the oxygen has been allowed to sweep out the train for two minutes after the fusion has taken place, the gas is turned off and the boat removed. The absorption bulb is removed, wiped dry, and weighed, and the percentage is calculated in the usual way from the gain in weight of the bulb.

Estimation of Oxygen in Iron and Steel.—J. R. Cain and E. Pettijohn (*United States Bureau of Standards*, 1919, Technologic Paper, 118) show that the Ledebur method for the determination of oxygen in iron and steel requires extraordinary precautions to obtain reliable results. The Ledebur method as described determines with certainty only oxide of iron, oxides of manganese (above MnO), and the oxides of nickel, copper, and tungsten if the latter three ever exist in steel. In turn such oxides are determined correctly only in case they exist in the metal uncombined as silicates, which probably seldom happens. The Ledebur oxygen determinations show no distinguishing features for acid Bessemer, basic or acid open-hearth, duplex, electric, or crucible steel, and shows no difference in steels deoxidised with a variety of deoxidisers.

Estimation of Phosphorus.—C. M. Johnson (*Chemical News*, March 7, 1919, vol. 118, pp. 113–115) gives a method for the determination of phosphorus in vanadium steel, ferro-vanadium, non-vanadium steel, and pig iron. It is claimed that the method is simpler than the old acid molybdate method and the interference of vanadium prevented. The method involves re-solution of the molybdate precipitate and titration with standard caustic soda solution, using phenolphthalein solution as an indicator.

Estimation of Sulphur.—H. J. Phillips (*Iron and Coal Trades Review*, January 10, 1919, vol. 98, p. 41) describes and illustrates a simplified form of apparatus for the rapid evolution method for the estimation of sulphur in iron and steel. The apparatus consists merely of an Erlenmeyer flask, into which is fitted through a rubber stopper a group of bulbs so constructed as to ensure the complete assimilation of the sulphuretted hydrogen evolved, by any of the well-known absorbents, without fear of the liquid being ejected out of the bulbs or sucked into the flask on cooling after the reaction is completed.

Estimation of Tungsten.—F. W. Foote and R. S. Ransom, jun. (*Engineering and Mining Journal*, May 4, 1918, vol. 105, p. 836) describe a method for the rapid estimation of tungsten.

Estimation of Uranium.—A convenient method for the determination of uranium in alloy steels and ferro-uranium is described by G. L. Kelley, F. B. Myers, and C. B. Illingworth (*Journal of Industrial and Engineering Chemistry*, April 1919, vol. 11, pp. 316–317).

Speeding up Metallurgical Analyses.—H. C. Parish (*Chemical and Metallurgical Engineering*, September 28, 1918, vol. 19, pp. 505–508) gives a number of hints for speeding up the analyses of various metallurgical products. For combining maximum speed and maximum accuracy in iron and steel analysis the use of the following methods, which are briefly outlined, is advocated:

Silicon.—Brown's method.
Manganese.—Bismuthate-arsenite.
Phosphorus.—Alkalimetric titration of the ammonium phosphomolybdate.
Carbon.—Direct combustion at 1000° C. and absorption of CO_2 in 12-mesh soda lime containing 15 per cent. H_2O.
Sulphur.—Evolution method and precipitation as cadmium sulphide. Titration with standard iodine.
Chromium.—A modification of Barba's process.
Nickel.—A modified cyanide method.
Vanadium.—Johnson's method, titrating with ferrous ammonium sulphate and using KFeCy as an indicator.
Tungsten.—Blair's method (Seventh Edition, p. 204).

H. C. Kimber (*Ibid.*, pp. 512–515) describes, with the same object, a carbon-combustion process employing barium hydroxide solution as an absorbent, and a method for the determination of chromium in high-speed tool steel, using silver nitrate solution and ammonium persulphate and titrating with standard permanganate.

ECONOMICS.

Iron Ore Supplies for Scottish Iron Trade.—H. A. Wilson (*Journal of West of Scotland Iron and Steel Institute*, January 1919, vol. 26. pp. 50–60) considers the position of the Scottish iron and steel trade in relation to basic ore supplies. The chief sources abroad to which the industry will have to look for future supplies are Normandy, the minette district of Lorraine, Scandinavia, and Newfoundland. Analysis of ores from these regions are given. Some interesting notes on handling and unloading ores in Scottish ports are given, and the importance of making adequate arrangements for the discharge of vessels is emphasised.

Ore Supplies for Midlands.—W. G. Fearnsides (*Lecture delivered before the Staffordshire Iron and Steel Institute*, March 6, 1919; *Iron and Coal Trades Review*, March 14, 1919, vol. 98, p. 327) deals with mineral supplies at blast-furnaces in the Midlands.

French Steel Industry during the War.—L. Guillet (*Bulletin de la Société des Ingénieurs Civils; Mémoires*, 1918, Series 8, pp. 208–226) reviews the condition of the French iron and steel industries before and during the war, and their future prospects. As compared with the resources available in 1913, the position during the early part of the war is shown in the following table:

	Output of Invaded Zone.	Output of Zone of Operations.	Output available after the Battle of the Marne.
	Per Cent.	Per Cent.	Per Cent.
Coal	50	24	26
Iron ore	83	9	8
Pig iron	62	19	19
Steel	58	15	27
Copper	94	...	·6
Lead	22	...	78
Zinc	76·5	...	23·5

Wages of German Miners.—A table is published showing the average wages earned per shift by miners in Prussia in the second quarter of 1918, and the percentage increase on the wages paid in the corresponding period in 1914. The figures are given for coal, lignite, and metalliferous ores raised in the principal mining districts of Prussia.

(*Iron and Coal Trades Review*; October 18, 1918, vol. 97, p. 429; from *Deutscher Reichsanzeiger.*)

The Iron Industry of the Ukraine.—H. Klein (*Stahl und Eisen*, September 19, 1918, vol. 38, pp. 868–871) reviews the conditions of the iron industry in the Ukraine in 1916–1917, including the supplies of raw materials, the production, the labour conditions, and the financial prospects.

Base Metal Industry.—B. Neumann (*Glückauf*, January 5, 1918, vol. 54, pp. 6–14, 21–27, 36–39, 45–52, 64–68, 77–82) reviews the position of the metal industry in the several producing countries in 1916. Comparative figures of the production, import, and export of the various base metals are given, with notes on the progress of methods of extraction and refinement of the metals.

Iron and Steel Industry in Japan.—A report on the present position and future prospects of the iron industry of Japan, Manchuria, and Korea has been prepared by Messrs. Suzuki and Goshima for the Imperial Railway Board of Japan (*Mining Magazine*, November 1918, vol. 19, p. 280). The enterprise at Lishan is known as the Anshanchan Ironworks, and the local iron mines from which the ore will be drawn are to the south-east of Ansantien station, on the South Manchurian railway, about 190 miles north of the port of Daisen and 60 from Yingkow. Two blast-furnaces are under construction, and the output is figured at 150,000 tons of pig iron per year. When the full scheme is realised, the output of pig iron will be 1,100,000 tons per year. The reserve of ore in the vicinity is estimated at 200,000,000 tons, and it is classed as hæmatite. The coal used will be brought from Pen-chi-hu, Kaiping, and Fushun, and eventually most will come from the last named.

The following are the producers, with figures for the last reported year's outputs:

	Tons.	
Japan.		
Edamitsu	281,977	steel
Kamaishi	57,425	pig and steel
Wanishi	29,970	pig
Sennin	3,796	,,
Kuriki	2,857	,,
Manchuria	45,000	,,
Total	421,025	

This figure represents about one quarter of the consumption of iron and steel in Japan for the current year.

The Edamitsu iron and steel works belong to the Japanese Government. The present capacity is 350,000 tons of steel per year, and is to be increased to 650,000 tons forthwith. Part of the ore or pig used comes from the Akutagawa mine in Japan, and part from the Tayeh mine in China. The Kamaishi enterprise at one time belonged to the Japanese Government, but is now owned by Chobei Tanaka. Next year a new blast-furnace will be in operation, and then the output of pig will be 155,000 tons. The Wanishi enterprise is now owned by the Hokkai Iron Company, and with the completion of two new furnaces, the output will be raised to 50,000 tons per year. The ore used comes from a local mine, and from China and Korea. The Sennin Company uses local ores, of which it has a reserve of 850,000 tons averaging 40 to 50 per cent. iron, and its yearly capacity is 4000 tons. Charcoal is used in smelting, and the pig, being of superior quality, is in demand at the arsenals. The Kuriki Company works under similar conditions on a limited scale. In addition to the above producers, there are a number of other enterprises in hand that will eventually increase the total output. The Mitsubishi Company has built a furnace at Kenjiho in north-west Korea near the port of Chinnampo. Both iron ore and coal are found in this district. The Okuragumi Hiroshima Company has lately completed a charcoal furnace in Japan with a capacity of 7000 tons, for producing special steel from Pen-chi-hu ores. The Toyo Company is about to erect blast-furnaces with a capacity of 150,000 tons per year at Kyushu, using ore from the Tao Chung mine in China. The Yasukawa foundry at Kurosaki will make steel from pig iron produced from Tayeh iron ores. The Han-yeh-ping Coal and Iron Company working in China is about to increase its capacity from 100,000 tons to 380,000 tons per year.

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NOTE ON THE INFLUENCE OF SOME ELEMENTS ON THE TENACITY OF BASIC STEEL.

(*In continuation of the Paper by* Dr. Andrew McWilliam, *published in the Journal of the Iron and Steel Institute*, 1918, No. II. pp. 43-55.)

The following table shows the results of tests on Indian basic steel, compared with those given by the formula in the paper referred to above. For the compilation of this table the author is indebted to Mr. C. H. Philpott, who has for several years, as Head of the Testing Department, represented Messrs. The Tata Iron and Steel Co., Ltd., Sakchi, Kalimati, B.N. Rly., while the author was representing the Government of India as Metallurgical Inspector.

At the author's suggestion, Mr. Philpott, who took great interest in the formula, has made this list of recent tests with carbon from 0·15 to 0·70 per cent. The examples chosen are not unfavourable to the formula, but all the actual tests were carefully made on a 100-ton horizontal Buckton testing machine. The analyses given were made on the actual test-pieces.

Analysis of Test-Piece.						Section Rolled.	Tensile Strength by Formula.	Actual Tensile Strength.
No.	C.	Si.	Mn.	S.	P.			
1	0·15	...	0·43	0·036	0·052	¾" rds.	26·5	26·8
2	0·16	...	0·49	0·025	0·030	Billets.	26·1	26·5
3	0·17	...	0·55	0·033	0·046	6" × 6" × ½" angles.	26·8	26·2
4	0·18	...	0·57	0·029	0·026	1¼" diam. rds.	27·1	27·2
5	0·19	...	0·57	0·028	0·028	9" × 4" channel.	27·5	26·9
6	0·20	...	0·59	0·030	0·029	,, ,,	28·0	27·7
7	0·21	...	0·58	0·031	0·018	⅞" rds.	28·0	28·6
8	0·22	...	0·58	0·030	0·023	1¾" squares.	28·5	28·9
9	0·23	...	0·58	0·026	0·031	2½" × ½" flats.	29·3	29·2
10	0·24	...	0·48	0·023	0·016	Billets.	28·6	28·7
11	0·25	...	0·61	0·035	0·040	¾" rds.	30·6	30·3
12	0·26	...	0·52	0·029	0·019	Billets.	29·7	28·6
13	0·27	...	0·59	0·045	0·038	3" × 3" × ⅜" angles.	31·0	30·9

Analysis of Test-Piece.						Section Rolled.	Tensile Strength by Formula.	Actual Tensile Strength.
No.	C.	Si.	Mn.	S.	P.			
14	0·28	...	0·67	0·038	0·030	½" rds.	31·7	32·0
15	0·29	...	0·63	0·028	0·016	5" × 3" × ½" angles.	31·3	31·0
16	0·30	...	0·61	0·039	0·028	6" × ⅝" flats.	32·2	32·5
17	0·31	...	0·55	0·024	0·020	½" squares.	31·4	31·3
18	0·32	...	0·53	0·032	0·022	1½" diam. rds.	31·4	31·5
19	0·33	...	0·71	0·030	0·039	6" × 3" channel.	34·4	34·4
20	0·34	...	0·70	0·027	0·029	Fish bolts.	34·4	35·6
21	0·35	...	0·62	0·031	0·039	„ „	35·0	35·5
22	0·36	...	0·69	0·029	0·031	6" × 6" × ⅝" angles.	35·4	35·1
23	0·37	...	0·66	0·024	0·051	⅝" squares	36·6	37·3
24	0·38	...	0·60	0·045	0·028	Billets.	35·7	36·4
25	0·39	...	0·59	0·038	0·035	⅝" squares.	36·4	37·7
26	0·40	...	0·68	0·031	0·020	¾" rds.	36·6	36·9
27	0·41	...	0·53	0·038	0·046	⅞" rds.	37·6	38·0
28	0·42	...	0·50	0·032	0·047	4" × ⅝" flats.	37·9	37·9
29	0·43	...	0·60	0·040	0·038	Billets.	38·5	38·1
30	0·44	...	0·57	0·040	0·042	6" × 3" channel.	39·0	38·3
31	0·45	0·03	0·78	0·027	0·028	1⅛" diam. rds.	41·6	42·2
32	0·46	...	0·54	0·038	0·039	6" × 3" channel.	36·9	36·3
33	0·47	0·02	0·78	0·027	0·037	1¾" diam. rds.	42·9	43·8
34	0·47	0·20	0·89	0·033	0·027	7" squares	44·3	44·3
35	0·48	·0·03	0·66	0·034	0·019	Billets.	40·3	40·0
36	0·49	0·03	0·84	0·055	0·063	Rail head.	45·4	44·8
37	0·50	0·03	0·65	0·039	0·034	1⅛" diam. rds.	43·4	44·0
38	0·51	0·03	0·69	0·029	0·027	2" diam. rds.	43·8	43·5
39	N. 0·52	0·03	0·59	0·037	0·029	Rail head.	43·8	44·7
40	N. 0·53	0·03	0·72	0·038	0·029	2" diam. rds.	45·5	44·5
41	N. 0·54	0·03	0·56	0·030	0·028	Rail head	44·5	43·9
42	N. 0·55	0·04	0·67	0·030	0·026	„	45·7	44·6
43	N. 0·56	0·02	0·79	0·027	0·034	„	47·7	48·5
44	N. 0·57	0·04	0·69	0·032	0·043	„	46·7	47·9
45	0·58	0·03	0·70	0·041	0·035	3" × ¾" flats.	47·9	47·5
46	N. 0·59	0·02	0·73	0·043	0·038	Rail head.	48·7	47·9
47	0·60	0·02	0·65	0·034	0·046	„	49·1	48·2
48	N. 0·61	0·03	0·55	0·024	0·017	„	47·7	49·2
49	N. 0·62	0·02	0·77	0·043	0·030	„	50·3	48·7
50	N. 0·63	0·02	0·69	0·035	0·021	„	49·8	50·7
51	N. 0·64	0·03	0·79	0·037	0·035	„	51·7	51·2
52	N. 0·65	0·02	0·68	0·028	0·016	„	50·7	51·9
53	N. 0·66	0·01	0·65	0·031	0·020	„	51·2	53·5
54	N. 0·67	0·02	0·69	0·036	0·015	„	51·8	52·7
55	N. 0·68	0·02	0·77	0·040	0·034	½" diam. rds.	55·5	56·4
56	N. 0·69	0·02	0·60	0·035	0·024	Billets.	54·1	54·8
57	N. 0·70	0·03	0·65	0·032	0·043	„	55·9	56·8

[The MS. of this Note was received too late to enable it to be incorporated in its proper place in Section I.—EDITOR.]

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